Chapter 5
Forest Plantations: Policies and Progress

Logging in the Tropics is commonly followed by deforestation and agriculture that degrade the soil, precluding subsequent continuous cultivation or pasturing. Agriculture persists on the best sites, leaving the poorer ones to return to forests. Of these, the best may be suitable for forest plantations.

The growing need for plantations was recognized decades ago by Champion (1949). He pointed out that there are many millions of hectares of land that should be afforested as soon as possible for society's benefit. He further stated that although the technology to restore forests may be based on incomplete understanding of the underlying principles, the work must proceed in the light of existing experience. His plea is still valid.

The ultimate extent of forest plantations in the Tropics will be determined by the degree to which they can compete with other land uses, meet growing demands for wood, outproduce alternative wood sources, and protect the environment for future generations. In spite of the uncertainty of long-range predictions regarding these stipulations, forest plantations have recently attracted far more interest and investment than the management of natural forests, primarily because of their reported high productivity potential. These and other matters pertinent to the decisions as to whether, how much, and what to plant are reviewed in this chapter.

Earl (1972) described how emphasis on commercial gain has led to shorter tree rotations and even-aged, pure stands (plantations). He foresaw that wood for fuel will be increasingly in demand for at least 50 years, even if an infinite source of pollution-free energy can be found.

The Food and Agriculture Organization (FAO) (Anon. 1981g) summarized the need for forest planting as follows:

- The current deficit in fuelwood in the Tropics is estimated to equal the production of nearly 48 million ha of fuelwood plantations.

- About 30 million ha of intensively managed, tropical hardwood plantations would be needed to meet the expected demand for sawlogs currently being harvested from primary tropical forests.

Ladrach (Anon. 1985f) further pointed out the greater labor requirements of forest plantations as compared with traditional grazing. Taking pine pulpwood on a 15-year rotation as an example, he concluded that employment is nearly 5 times greater in forest plantations than in pasture production, and yet the forest may be grown on poorer soils.

Two valuable references on forest plantations in the Tropics are available. Evans (1992) emphasizes the planning of plantations, taking into account social and economic factors and describing practices from establishment to harvest. Zobel and others (1987) clarify misunderstandings concerning exotic species and document the high yields attainable through plantation tree improvement.

The Case for Planting

The case for planting rests partly on land availability and foreseen timber shortages. One analysis concluded that plantations are needed where: (1) natural forest area is inadequate, (2) natural forests grow too slowly to meet bulk forest-product demands on a sustained-yield basis, (3) natural forests are too scattered to permit economical harvesting, and (4) natural forest timber is too remotely located to be transported economically (Marsh 1962). All of these problems were said to be avoidable by establishing plantations of fast-growing species near communities and processing industries.

Evans (1992) supported plantations by contrasting negative and positive factors. Negative factors include past and continuing destruction of the native forests, decreasing access to remaining forests, and unsatisfactory natural regeneration. Positive factors are increasing land availability, high productivity, the potential of current plantations, and environmental benefits.

A review of the situation in Nigeria showed the close relation between land availability and reforestation needs (Lowe 1984). There, even though only about 10 percent of the country was reserved for forests and most of this is poorly stocked savannas, encroachment by farmers could be prevented only by planting exotic tree species on threatened areas. The best reserved forests, some 2,000 km^2 of which were formerly under a shelterwood system, have been converted to plantations to increase productivity. A national plan described in 1985 was to plant over a 20-year period half the high forest reserves and one-tenth of the savanna reserves, even though doubts remain as to successful techniques.

Wadsworth (1983) analyzed the potential environmental benefits of expanding timber plantations. For the Tropics as a whole, he calculated the prospect for reducing the demand for timber from natural forests by increasing the timber supply from plantations (table 5–1).

Public concern over planting proposals, even where reforestation is itself favored, must be addressed. A prime example is the opposition to the planting of eucalypts. This opposition is most evident in the Eastern Hemisphere but has existed throughout the long history of planting these species in Brazil. The complexity of this matter is to be seen in the scope of arguments used against eucalypts, summarized by Spears (1987) as follows:

- Eucalypts, as nonleguminous species, deplete nutrients.
- Eucalypts jeopardize the hydrological water balance.
- Eucalypts have allelopathic effects on some farm crops.
- Eucalypts usurp good farm land.
- Eucalypts require less rural employment than other crops.

In part, these concerns reflect problems with eucalypts planted in the wrong place. But to a larger degree, they are generalizations without much factual basis. Clearly, there is a need to inform the public about any possible deleterious effects of eucalypts (or any other plantation species) together with the prospective benefits in terms of rapid growth, timber and fuel supplies, forage values, protective values, employment, and economic returns. This subject was treated in depth by Poore and Fries (1985).

Productivity Advantages of Plantations

The superiority of plantations over natural forests as a source of timber rests primarily on their higher productivity of marketable wood. The advantages of plantations are most evident where natural regeneration is deficient, where native trees are of limited utility, and where differences in growth rates are pronounced.

Other reasons for planting include the need to rehabilitate deforested land (Baur 1964b). Further, there is growing pressure to replace natural forests, perceived by the public as jungles, which contrast unfavorably with nearby agriculture that is increasingly in demand and producing greater economic returns.

The failure of prompt, natural regeneration of desired timber species is common on land farmed and abandoned. Moreover, under some circumstances, useful, natural, tree regeneration has proved almost impossible to achieve. One instance is that of *Araucaria angustifolia*, the "pino" of southern Brazil. Because it does not regenerate well naturally, plantations of this and other species of pines are preferred to the natural forests (Krug 1968).

Natural regeneration, even where adequate, may promise only fuelwood rather than industrial wood. Except where fuel is extremely scarce, this prospect dooms naturally regenerated forests to low economic yields. Successful plantations on the other hand, offer greater certainty as to composition, quality, yield, and timing of the next crop.

Table 5–1.—Plantation timber as a substitute for natural forest timber in the Tropics

Requirements currently met by plantations (%)	Timber source needed to meet demand in the year 2000[a] (million km^2)		Reduction in natural forest cutting[a] (million km^2)
	Available from plantations	Natural forests required	
12	0.2	6.0	0.6
20	0.4	5.5	0.9
30	0.5	4.8	1.5
50	0.9	3.4	2.5
100	1.7	0.0	5.1

Source: Wadsworth 1983.
[a]Estimated.

That natural forests grow slower than plantations throughout the Tropics is of concern. Most comparisons are somewhat biased, however; often they are made between leftover trees of unknown ages and histories in cutover forests and young, well-spaced, well-cared-for trees in plantations. Other inequalities may prevail, such as site quality, market value per unit of volume, and completeness of utilization. Despite all these, trees in plantations generally produce more usable wood than do trees in natural forests.

Growth of trees in native forests in Brazil showed them to be no match for planted eucalypts (Navarro de Andrade 1941). In Mauritius, the indigenous trees of mountain forests were found to be slow growing (King 1945), and in Kenya, the growth rate was so slow that the regeneration of native species by either natural or artificial methods was considered uneconomical (Dyson 1965).

The implications of growth-rate differences between naturally regenerated and planted forests are spectacular in terms of crop rotation. A review of silviculture in Nigeria (Wyatt-Smith 1968) led to the conclusion that replacing natural forests with plantations of species of the genera *Khaya, Lovoa, Tectona, Terminalia,* and *Triplochiton* (native to the region) might reduce the rotation to 60 cm in diameter at breast height from 100 to 50 years.

In Malaysia, plantations of budded rubber 81 months old have produced a phytomass of 20 tonnes per hectare per year, converting 2.5 to 2.8 percent of visible radiation (Wycherley 1969). Productivity (above and below ground) of oil palms in plantations ranges from 30 to 37 t/ha/yr. At high altitudes, planted conifers and eucalyptus, indigenous or introduced, attain 13 to 40 t/ha/yr, a level of production that could not possibly be attained by the natural forest communities that such crops replaced (Dawkins 1967). Retaining natural forests on the grounds of productivity is seen as questionable, although a much stronger case can be made where other values, such as soil or water conservation, are important (Wycherley 1969).

Added arguments for tropical plantings are based on their superiority as a source of wood supply over plantings in the Temperate Zone (Machado 1977). Average conifer yields are 5.3 t/ha/yr in the Temperate Zone versus 12.6 t/ha/yr in the Tropics. For broadleaf species, the corresponding averages are 5.1 t/ha/yr and 13.1 t/ha/yr.

An early report from Uganda (Laurie 1962) cited natural forest production of 0.7 m^3/ha/yr, yet nearby *Eucalyptus* produced more than 40 m^3/ha/yr. Dawkins (1964b), after a regionwide review, concluded that managed, moist tropical forests might attain 4 to 10 t/ha/yr of stemwood versus 14 to 24 t/ha/yr for conifer or eucalypts plantations. Natural coniferous forests in the Tropics are rare, but under favorable circumstances, such forests can produce stemwood volumes of 35 m^3/ha/yr (Wood 1974). In the miombo forests of Nigeria, Jackson (1973) reported a yield of 1.4 m^3/ha/yr for a native *Isoberlinia* forest versus yields to 24 m^3/ha/yr for six plantation species.

Fuelwood produced in plantations can be a viable alternative to petroleum. Petroleum equivalents for 7-year-old *Eucalyptus* in Africa from the Centre Technique Forestier Tropical relative to rainfall are presented in table 5–2 (Catinot 1984).

Studies of the U.S. National Research Council (Anon. 1984c) indicate that agroforestry and improved charcoal production and use are among the most promising prospects for increasing energy production. With the development of practical systems to convert lignocellulose in wood to alcohol, charcoal plantations may compete with farming for arable land.

The average productivity of plantations of various tropical tree species is summarized in table 5–3 (Evans 1992). An analysis in 1980 (Brown and others 1986) showed that plantations constitute less than 2 percent of the organic matter in tropical vegetation, but their biomass per unit of land area (123 t/ha) averages more than that of natural tropical forests (106 t/ha).

Table 5–2.—Petroleum equivalent of 7-year *Eucalyptus* yields in Africa

Mean annual precipitation (cm)	Wood yield (m^3/ha/yr)	Petroleum equivalent (t/yr)
30–60	3–4	0.7–0.8
60–80	4–8	0.8–1.6
80–100	15–25	3–5
>100	25–80	5–10

Source: Catinot 1984.

Table 5-3.—Productivity of tropical plantations

Species	Rotation (yr)	Yield (m^3/ha/yr)
Paraserianthes falcataria (Philippines)	10	28
Eucalyptus		
Subtropical	8–25	5–30
Tropical	7–20	≤60
Gmelina arborea (Brazil)	10	35
Pinus caribaea (Fiji and Brazil)	8–16	21–40
P. patula (Africa)	15–16	18–19
Swietenia macrophylla (Fiji)	30	14
Tectona grandis	40–80	4–18

Source: Evans 1992.

There is a serious need for more precise descriptions of plantation performance. Qureshi (1968a) noted the lack of clear specifications as to the size and quality of the material yielded and the precise period in which it is obtained. These deficiencies are exemplified by the studies reviewed, some of which present data in cubic meters, others in tonnes, often with no rotations or size limits specified. In a study of 502 timber plantations in tropical America (Lugo and others 1988), the data were adequate and comparative for only 8 tree species. Some data were for too short a growth period, and thinnings were not accounted for. In addition, the status of bark was not specified nor were the utilization limits.

Malcolm (1979) concluded that the structure of plantations resulted in a higher percentage of usable wood in plantation trees than in natural forest trees. In comparing a natural forest and a 35-year-old plantation of *Shorea robusta* in India, Raman (1975) found that 92 percent of the aboveground phytomass in the plantation was in usable stemwood compared with only 71 percent in the natural forest.

Land Considerations. With land increasingly in demand for other uses, the shift from the lower productivity of natural forests to plantations has become commonplace. In Kenya, a major motive for shifting to plantations has been to concentrate production on a smaller area, because forest area was being lost to other uses (Dyson 1965). In Nigeria, transition has taken place from natural methods through *taungya* to intensive plantations in the face of growing competition from other land uses (Lowe 1977).

In Puerto Rico, it became evident early that unless timber yields per unit of land area could increase as rapidly as adjacent agricultural productivity, land use would increasingly favor agriculture (Wadsworth 1961). Baur (1964a) concurred, concluding that forestry will ultimately be confined to smaller areas and that intensified management is inevitable. He noted that export timbers yield less profit than cocoa or rubber and emphasized the growing need for more forest plantations.

Economic arguments for plantations have been presented for many years. Beresford-Pierse (1962) saw a need to change the prevailing view that more natural forests should be managed. The difficulty of utilizing inaccessible or complex forests can make the wood extracted from them so expensive that it becomes uneconomical, he argued. Vast areas of land would thus be unsuitable for management because of this high cost. He favored depending more on genetics, fertilization, cultivation, and integration with farming.

Ovington (1972) emphasized the need to consider plantation location, product requirements of industry, and the economics of management. A complicating factor is the large plantation area necessary to support processing industries. Evans (1992) estimated the minimum size of plantations needed to support various wood-using industries and the employment each would generate (table 5–4).

The selection of land for planting should also be sensitive to site quality because it affects potential tree growth. Contrasts between good and mediocre sites are shown in table 5–5.

The choice between natural regeneration and planting is not always easy. Where there is doubt, Synnott and Kemp (1976) favored the "greater robustness" and long-term security of maintaining natural forests. Nevertheless, they agreed that, where land is limited and greater production is essential, plantations are indicated. They further saw that planting should be concentrated on nonforested, degraded lands (provided of course, that the sites are not submarginal for practical forest production).

Wood (1974) saw three land-use choices in countries with extensive primary forests: (1) conserving naturally

Table 5–4.—Minimum tropical plantation size to support wood-using industries

Operation	Annual wood requirement (m^3)	Plantations needed (ha)	Human resources (no. of jobs)
Sawmilling	15,000	1,000	30
Integrated sawmilling and plywood	100,000	7,000	200
Integrated pulping	500,000	25,000	2,000

Source: Evans 1992.

regenerated forests and management on long rotations, (2) increasing naturally regenerated forest yields and shortening the rotation by silvicultural treatment, or (3) replacing naturally regenerated forests with "compensatory plantations." For countries without extensive forests, plantations were considered inevitable. In Ghana, it was concluded that 1 percent of the original forest area converted to timber plantations could equal the former yield of the native forests (Foggie 1957).

Leslie (1967) points out that a cost-benefit analysis of the decision between plantations and natural regeneration could favor natural forests when watershed, recreation, wildlife, and floral values are factored in. These values are seldom assessed in such decisions.

Limitations of land capability present a convincing argument for reforesting cleared land within much of the Tropics, whether for timber or other tree crops. Goodland (1986) sees the most sustainable development for Brazil's Amazonia to be forest based. He proposes a mixture of perennial crops and subsistence cultivation of annual crops. Extracting the most valuable timber with concomitant silviculture could provide the capital for development. Other tree crops recommended by Goodland were rubber, oil palms, cocoa, Brazil nuts, coconuts, coffee, and babassu.

Throughout the Tropics, most plantations have been established on former grasslands and savannas (table 5–6; Evans 1992). Scrub woodland is the second most common type of land used for plantations in tropical America, but in Africa and Asia, it is the rain forest type.

Timber Supply

Even where land for forests is plentiful, intensification of management may still be called for because of increasing inaccessibility or deficient quality of the remaining native timber supplies. Concern for the wood supply led to the first efforts to plant teak in Malabar in 1830 (Laurie 1937). In Thailand, fuelwood plantations followed a twentyfold rise in fuelwood prices (Thirawat 1952). In Uganda, doubts concerning the adequacy of naturally regenerated forests led to timber plantations on the grasslands (Anon. 1957e).

By 1959, the only hope seen for a substitute for dung as fuel in India lay in the production of 3.4 million m^3 of fuelwood each year (Ishaq 1959). By 1975, demand for both wood and land left no alternative but to increase production in existing forest areas (Singh and Randev

Table 5–5.—Mean annual increment superiority of good over mediocre tropical planting sites for various species

Species	Age (yr.)	Superiority of good over mediocre site (%)
Araucaria angustifolia	30	105
Azadirachta indica	9	234
Cryptomeria japonica	30	117
Cupressus lusitanica	20	47
Eucalyptus camaldulensis	12	72
E. deglupta	12	20
E. globulus	12	118
E. grandis	12	139
E. saligna	12	122
Gmelina arborea	12	40
Pinus caribaea	20	28
P. patula	16	68
Swietenia macrophylla	40	120
Tectona grandis	65	123

Source: Evans 1992.

Table 5–6.—Land converted to tropical timber plantations

Previous status	Converted to plantations (%) America	Africa	Asia-Pacific	World
Grasslands and savannas	52	67	40	52
Scrub woodlands	25	6	11	16
Rain forests	4	18	34	15
Idle, deforested areas	18	3	8	12
Timber plantations	1	5	6	3
Other	0	1	1	2
Total	**100**	**100**	**100**	**100**

Source: Evans 1992.

1975). The demand for fuelwood called for rapid growth, and the need for construction timbers required plantations because of the excessive density and seasoning problems of the woods from native forests (Sahni 1965).

By 1973, it was seen in Nigeria that 12,000 ha needed to be planted annually to supply foreseeable national requirements (Oseni 1973). Fuelwood scarcity was most severe in the savannas where the productivity of native woodlands was low (Jackson 1973).

Timber scarcity has also spurred planting in tropical America. Trinidad, with no outstanding local species, converted to plantations. So did countries with land on high Andean slopes (Laurie 1962). Despite extensive remaining native forests in Suriname, plantations were being established on a large scale by 1966 because natural regeneration was deficient (Schulz and Rodriguez 1966). The need to plant was evident in the deficit of accessible timber anticipated for 1985. Reducing waste and using more species of the native forests were not expected to forestall this need (Dickinson 1967). In Brazil, where most timber is sold to processors, incentives were used to get plantations started (Dickinson 1967). In Peru, where wood consumption is largely rural and local, planting was undertaken without incentives, even though the crop took a decade to mature.

Planting has in some areas succeeded in solving problems. In Fiji, by 1984 the 38,000 ha of successful plantations were more profitable than tourism, sugarcane, or copra (Rennie 1974). In Brazil, one-third of the industrial wood raw material comes from plantations. By 1965, existing tropical plantations had the potential to supplant half the current annual drain of industrial roundwood from natural forests; at the then current rate of planting it was felt they could meet prospective cellulose demand by the year 2000 (Anon. 1965e).

Teak in Trinidad, introduced in 1913, now covers more than 5,000 ha. These plantations fostered the creation in 1978 of the Trinidad and Tobago Forest Products Company Ltd. and are expected to produce a sustainable annual yield of 18,000 to 24,000 m^3 of teak poles and 34,000 to 57,000 m^3 of teak sawtimber (Anon. 1982c).

Lanly (1982), in his worldwide inventory of tropical forests, distinguishes the following two types of forest plantations based on their objectives:

- Industrial plantations, established totally or partly to produce wood used mainly for pitprops but also for sawlogs, veneer logs, and pulpwood

- Other plantations, established to produce fuelwood or charcoal wood (possibly for industrial use), wood for domestic (in particular rural) consumption, fruits, palm hearts, gum arabic, cinnamon, etc.; and to protect the soil

About half the forest plantations of the Tropics are devoted to the production of industrial wood (table 5–7; Evans 1992). Fuelwood is the next most common product, accounting for 18 percent of the tropical plantations worldwide and 29 percent in America.

Wood (1976) pointed out that the apparent capability of stable high forests to supply human needs in perpetuity is not commercially feasible, even using labor paid at the lowest rates. The high cost of wood harvesting, whether

Table 5–7.—End products of tropical forest plantations and percentage of forest land area devoted to production of each

Primary end use	Forest land area (%) World	Forest land area (%) America
Industrial wood	54	50
Fuelwood	18	29
Protection	17	10
Minor products, agroforestry, other	11	11
Total	**100**	**100**

Source: Evans 1992.

by hand or machine, demands that as many trees as possible be felled at each harvest. This operation disturbs the ecosystem so much that the resulting regeneration rate cannot sustain the forest, particularly after selective removal of the best trees. It is only by planting that the genetic quality of the original trees can be maintained or improved. Where forest land is in short supply, the production of wood is not by itself a strong enough argument for keeping natural, tropical forests (Wood 1976). There must also be benefits for soil, water, scientific study, genetic conservation, or secondary forest products.

In Malaysia, retaining mixed forests results chiefly in the production of cellulose; rapidly growing plantations could supply this product much more economically (Tang and Wadley 1976a, 1976b).

Some precautions are noteworthy in a shift to plantations. Such a shift calls for high performance and a quality crop from tree species usually grown far from their native sites. Zobel (1978) warns that it is a mistake to think that because the wood of a native species is good, it will be equally good when grown in a different habitat. He notes that any silvicultural treatment undertaken to increase growth rates will affect the wood. Rapid early growth means juvenile wood at maturity. Crookedness in pines in the Tropics is not only common in plantations but may lead to "compression wood" (wood compressed beyond its elastic limit).

Hughes (1968a) reports that wood from *Pinus caribaea* plantations often has poorly developed latewood and thus may be much lower in density than naturally grown wood. This reduces its value for heavy construction but increases its value for joinery. Infiltration of the heartwood zone by resin and the common occurrence of compression wood are serious defects of rapidly grown trees. Spiral grain (twisted fiber) may also appear. The major differences between plantation wood and naturally grown wood appear to be related largely to climatic and site conditions (Hughes 1968a).

Studies of teakwood from plantations and from naturally grown trees have shown no significant difference in resistance to subterranean termites (Da Costa and others 1958). Resistance increased with tree age and wood extractive content. Tests of 51-year-old, rapidly grown plantation teak from India (1 to 3 rings per centimeter) showed it to be 15 percent weaker and 15 to 25 percent softer, but 12 percent stronger in tensile strength than more slowly grown Burmese teak (Wood 1968).

Legitimate concerns notwithstanding, plantations of high-value tropical woods (such as *Cedrela, Maesopsis, Tectona, Terminalia,* and *Triplochiton*) promise returns greater than most other investments in the countries where they grow (Spears 1980). Furthermore, the prospective wood requirements of a long and lengthening list of tropical countries can no longer be met by domestic sources other than plantations.

The widely used term "compensatory" plantations refers to plantings undertaken to produce at least as much timber as the natural forests they replace (Dawkins 1958g). Compensation usually requires planting a much smaller area than the forests being replaced.

Even where plantations are justified, it does not necessarily follow that all remaining naturally regenerated forests are best left unproductive. If they are, they become vulnerable to destruction; whereas they might still produce forest crops to supplement those of the plantations and continue to provide other values.

In a study of biomass energy needs in developing countries, the U.S. National Research Council (Anon. 1984c) concluded that when the price of petroleum fuels rises above the cost of biomass-based energy, the production of energy in tropical forests will attract those who have depended on petroleum for energy. These conditions already exist in many developing countries where increased biomass production is essential both to meet energy needs and to counter deforestation. Agroforestry and charcoal production were seen as promising energy technologies. Competition for arable land currently prevents adoption of large-scale fuel production in many areas. This was seen to be less of a problem as soon as practical systems to convert lignocellulose in wood to alcohol become available. Reforestation for fuelwood and charcoal, when properly managed, is expected to generate an attractive rate of return without a perpetual subsidy.

Site Considerations

Most plantations are more beneficial ecologically than nonforested areas. The ecological effects of plantations on the sites are similar to those of natural forests. A comparison of mineral cycling in Ivory Coast between a natural forest and a 38-year-old plantation of *Terminalia ivorensis* showed that leaffall and soil percolation were similar (Bernhard-Reversat 1976). The accumulation of organic matter and nitrogen (N) in the topsoil was actually greater in the plantation, but the exchangeable cation reserves of the soil were lower, particularly on sandy soils. The influence of plantations on the disposal of rainfall can be beneficial. For example, in a 93-week test in Brazil, a 13-year-old plantation of *Pinus caribaea* and *P. oocarpa* intercepted only 12 percent of the rainfall versus 28 percent in nearby cerrado vegetation (Lima and Nicolielo 1983).

Concern over the effects of plantations on sites has prompted many studies throughout the tropical world. In Trinidad, in *P. caribaea* plantations, total reserves of N decreased for 5 years but recovered by the 12th year (Cornforth 1970b). Phosphorus (P) reserves decreased slightly after the preparatory burning and although the availability of P in the soil increased through the 7th year, it had not regained its original level by the 12th year. Reserves of potassium (K), calcium (Ca), and magnesium (Mg) released by burning were rapidly lost by erosion and leaching.

The characteristics of the top 7.5 cm of soil in a 25-year-old plantation of neem *(Azadirachta indica)* in northwestern Nigeria compared with nonforested land are summarized in table 5–8 (Radwanski 1969).

In *P. radiata* plantations in subtropical Australia, soil N increased 50 kg/ha even where nodulated species were not present in the understory (Richards 1964). Rainfall contributed 10 kg/ha/yr, and free-living, N-fixing bacteria, about the same amount. Soil N was rapidly absorbed by the pines.

Table 5–8.—Soil characteristics of neem *(Azadirachta indica)* plantations compared with nonforested land in northwest Nigeria

Soil parameter	Nonforested	Plantation
pH	5.4	6.8
Carbon (%)	.120	.57
Total nitrogen (%)	.013	.047
Carbon-to-nitrogen ratio	9.4	12
Total phosphorus (ppm)	201	131
Potassium+ (meq/100g)	.08	.23
Calcium+ magnesium+ (meq/100g)	.29	2.15
Total cations (meq/100 mg)	.39	2.4
Base saturation (%)	20	98
Cation exchange capacity	1.7	2.4

Source: Radwanski 1969.

Note: Listed characteristics are means for values found at a depth of 0–7.5 cm depth.

In the Temperate Zone, the shift from broadleaf forests to conifer forests has increased N availability on the site over and above the intake of the pines (Stone and Fisher 1969). This effect, which extends beyond the area covered by the tree crowns, has been attributed to mineralization, not fixation. Accretion in N fixation has also been associated with the growth of pines (Wollum and Davey 1975).

An intensive study of plantation effects on the soil, including those in Belize, Brazil, and Suriname, as well as in west Africa, was made by Chijioke (1980). He concluded that in plantations of rapidly growing tree species in the lowland humid Tropics, harvesting of the stemwood plus bark removed 70 to 80 percent of the nutrients immobilized in the tree. *Gmelina* exports significantly more nutrients with rotations of 5 to 6 years than with rotations of 13 to 15 years. Leaving slash, as opposed to whole-tree harvesting, could reduce nutrient losses 25 percent. Leaving the bark could conserve an additional 5 to 10 percent. Chijioke found total N to be more than adequate despite the large quantities immobilized by *Gmelina* and pines.

Plantations may markedly benefit the water regime. Their influence on the disposition of rainfall is indicated by tests made in India with plantations of *P. roxburghii* and *Tectona grandis* (table 5–9; Dabral and Subba Rao 1968). The large amount of interception of light rains is impressive. Nevertheless, in subtropical Jodhpur, India, soil depletion at a depth of 10 cm 39 days after a rain was 76 percent under 3-year-old *Eucalyptus* and 92 percent under 11-year-old *Acacia,* compared to 86 percent under grass. At a soil depth of 60 to 90 cm, corresponding percentages were 36, 7, and 7 (Gupta and others 1975).

The apparently high productivity of *Eucalyptus* and *Pinus* plantations suggests that they draw heavily on soil water. But a study in Brazil indicates that they consume no more than herbaceous vegetation (Lima-Freire 1976). May-to-September evapotranspiration was 20.6 cm for a 5-year-old plantation of *E. citriodora,* 21.2 cm for a 5-year-old plantation of *P. caribaea caribaea,* and 19.6 cm for herbaceous vegetation. Conclusions to the contrary were reached by Poore and Fries (1985) to the effect that eucalypts decrease water yields more than grasses, herbaceous vegetation, and broadleaf tree species but less than pines. Eucalypts reduce runoff if thinned enough to conserve ground vegetation and if fires are excluded.

In Kenya, plantation softwoods managed on rotations of 20 or fewer years and subject to annual fellings consumed less water over a 10-year period than did a natural forest on a comparable site (Pereira 1967). However, the plantations did use about 10 percent more water than perennial pasture grasses.

Despite the fact that plantations are much less ecologically diverse than natural forests, in New South Wales, Australia (latitude 34° S.), mature *P. radiata* plantations 40 years old had as many or more birds as two indigenous forest types, but only about two-thirds as many species. The species of birds under the two conditions were different.

A mature plantation of *Araucaria cunninghamii* in Australia was similar to a rain forest in annual, mineral-element accessions to the soil (Brassell and others l980). This held true on fertile and infertile soils and on wet and dry sites, suggesting that if there were any site deterioration in the plantation, it would not be due to a reduction in mineral cycling during the later stages of the rotation.

The prospect of lowered yields as a result of site deterioration under intensive management of short-rotation, planted tree crops has been a concern of foresters for decades (Lamb 1969a). The use of light demanders on sandy soils was seen to be particularly risky. There is obviously a need to monitor continuing performance and to learn of any input needed to maintain levels of productivity during succeeding rotations (Evans 1976).

Much controversy has arisen in Australia over the different effects on sites of plantations versus native forests. Evidence does not yet strongly support appeals for natural forests (Anon. 1971–72). Evidence of decline in the second and third rotations in *P. radiata* plantations in South Australia is not yet convincing (Boardman 1978). In fact, there is overwhelming evidence that the productivity achieved by the time the canopy closes tends to be maintained. Silvicultural practices and weather appear to have great influence.

Studies of the oldest teak plantations in Nilambur, India, reportedly have shown no decline in height growth in the second rotation (Venkataramany 1960b).

A thorough study of second rotations of *P. patula* in Swaziland suggested no significant decline in site quality (Evans 1972). Second-rotation height growth was 90 to

Table 5–9.—Rainfall disposition by plantations of *Pinus roxburghii* and *Tectona grandis* in India

	Rainfall amount per storm (%)			
	1.35–2.5 cm		>5 cm	
Rainfall disposition	*T. grandis*	*P. roxburghii*	*T. grandis*	*P. roxburghii*
Interception	37	29	4	4
Stemflow	7	3	9	5
Throughfall	56	68	87	91
Total	**100**	**100**	**100**	**100**

Source: Dabral and Subba Rao 1968.

95 percent as rapid as that of the first rotation in 64 pairs of plots. Evans concluded, however, that there is no basis for assuming that growth of successive forest crops gradually declines. In the test area, rainfall was slightly lower during the early years of the second rotation. A 10-percent loss in fiber through less dense corewood was indicated, but this was conjectural. Of many site factors studied, however, none clearly caused the growth changes observed.

Soil N declined in second-generation *P. radiata* plantations in New Zealand (Stone and Will 1965). One theory is that the pine roots may be able to break down some fraction of the soil organic matter that is inaccessible or resistant to the previous flora. This capability would be an advantage to the first crop over the preceding vegetation (without pines), an advantage that would not be equally available to succeeding generations of pines.

In regions subject to hurricanes, plantations may suffer more general damage than natural forests (Brouard 1960). The plantations of *P. caribaea* in Jamaica suffered severely during the hurricanes of 1980 and 1988, whereas nearby natural montane forests were much less affected (Tanner and Kapos 1991). The ecological and economic consequences of storms may differ widely. A plantation of pines, even if severely affected, may represent fewer years of management and a higher productivity prior to the storm, much of which could promptly be harvested for posts and cellulose products. Storm effects on a mixed forest, even if superficially less severe, may result in breakage of trees on a longer rotation and of higher ultimate value per unit of volume than the pines. At intermediate size, with little heartwood and scattered in the stand, those species valued only for sawtimber are generally impractical to harvest.

Natural forests, according to Peace (1957), do not necessarily have fewer pathogens than plantations. He points out that every departure from nature is not bound to encourage diseases. Site and pathogens play differing roles in the occurrence of diseases. Foresters must not think that "unnatural" is the same as "unhealthy." Peace concluded that the greatest single factor in successful plant cultivation is the removal of competitors, something that seldom takes place in the natural environment.

In summary, although there is much evidence to show that tropical forest sites deteriorate after deforestation, there is little to suggest further decline from successive timber crops. Research indicates that such a decline has not yet occurred to any significant degree (Bednall 1968; Evans 1972; Laurie 1934, 1941b). However, the nutrient drain implicit in repetitive cropping, particularly on short rotations, may be sufficient to bring on such a decline, presumably toward a lower nutrient-level plateau corresponding to the natural rate of replenishment.

Plantation Planning

Ladrach (Anon. 1985f) used experience in Colombia to formulate guidelines for establishing industrial-forest plantations and suggests that the following items be considered in preliminary planning:

Community relations	Nursery establishment
Land tenure and acquisition	Site preparation
Mapping	Fertilization
Protection of existing natural forests	Spacing and stand density
Boundary maintenance	Planting procedures
Road and firebreak layout	Fire control
Species selection	Pest control
Rotation length	Recordkeeping
Yield estimation	Personnel training
Seed supply	Development of contractors

He lists the major industrial-plantation risks as wildlife, pests, wrong species selection, inadequate seed supply, nursery and planting problems, poor wood quality, and inadequately trained personnel. He concludes that most of these risks can be reduced by proper planning, organization, and research.

Lewis (1968) predicted that although natural regeneration might continue where planting is most difficult, such as on mountains, large areas of timber plantations will be established in the Tropics because of increasing concern for the time, cost, and control of natural regeneration. Genetically improved stock will not be wasted on poor sites, and replacement of slow-growing species with rapid growers will continue, even if the new species are not as well adapted and need fertilizer. Research will have to show how far this process can be permitted to proceed without risk. A remaining question is how to stabilize production after the first crop.

Interplanting. Forest planting usually means establishing tree crops on deforested land. But in the Tropics, planting is also commonly done within existing forests. Such plantings are believed to re-create an environment similar to that experienced in nature by young trees entering the forest ecosystem. The forest left after partial cuttings has been thought to protect recently planted trees. Planting within an existing forest may also be less costly because part of the residual stand may be suited for the next crop.

Trees are planted in existing forests either for "enrichment" or "gap planting," which is the filling in of natural gaps in forest regeneration, or as "underplanting," the planting of young trees or the sowing of tree seeds, usually spaced systematically under most or all of an existing forest (Ford-Robertson 1971).

In Nigeria, enrichment began in 1927 (Wholey 1955) to maintain a stable forest environment and to avoid the cost of land clearing. Brasnett (1949) concluded that the practice is appropriate where natural regeneration of desired species is deficient and cannot be adequately induced by known silvicultural methods. It is also appropriate where so few trees can be sold per unit of land area that gradual freeing of scattered regeneration requires more skilled supervision than is justified. He suggested that planting should be done systematically, in lines, to facilitate tree relocation. Because adequate overhead light can be provided at the time of planting, the species planted may be light demanders. He also recommended the use of planting stock 2 to 3 years old, seedlings that have survived the difficult, early developmental stages in the nursery.

In Papua New Guinea, different intensities of enrichment have developed (White 1976b). The least intensive practice, termed "opportunity enrichment," involved planting only the logged openings where no further clearing is needed. Where practice was more intensive, all gaps are planted, and between them a stand of overstory trees of good species 45 to 60 cm in d.b.h. was thinned to preserve a spacing of approximately 60 by 60 m as a crop and for future seeds.

Gap Planting. Gap planting has been the most common form of enrichment. Gaps occur in cutover forests where several trees close together have been felled, at landing sites, or where charcoal burning has destroyed all natural regeneration (fig. 5–1). Gap plantings were tested as an inexpensive way to supplement the next crop. One of the arguments for the practice is that "nothing else will come up and that there is a need to husband a forest or lose the land to other uses" (Laurie 1934). Gaps are generally larger than 300 m². The undergrowth

Figure 5–1.—*Gap planting, or forest enrichment, using pines on the slopes of Jamaica.*

may be burned. Teak may be planted at 1.8 by 1.8 m near the center of the gap.

In Uganda (Earl 1968), charcoal kiln sites were planted at a spacing of 100 trees per hectare, with trees set at 20 m or more from the edge of the nearest adolescent crown. Planting was done as soon as the charcoalers leave in order to minimize the need for weeding. Two trees were planted per spot; one of the pair was removed after 1 or 2 years. Species used have included *Burtdavyia nyassica, Cedrela odorata, Maesopsis eminii, Nauclea diderrichii, Terminalia ivorensis,* and *T. superba.*

Experience in India and west Africa with gap planting led to its early demise. In India, gap planting was tested in various provinces as early as 1934 (Laurie 1941b), but gaps proved difficult to tend because of the scattered distribution of the trees (Griffith 1941b). Even when they no longer need tending (after 2 years), gap plantings are wasteful in that the overall crop may be poor. By 1941, gap planting had been abandoned in India (Laurie 1941b).

In west Africa, gap planting was tried after close planting beneath the canopy (2 by 2 m) failed because of inadequate light (Wholey 1955). The planting of gaps, however, was found to leave poorly regenerated areas between the gaps. The relocation of all but the largest gaps was difficult, and repeated clearings proved costly (Catinot 1969b, Foggie 1957, Laurie 1934a). At best, gap plantings have been considered wasteful in that they produce less than concentrated plantations might on better soils.

Gap plantings have been practiced in the dipterocarp forests of the Philippines, where they prevent postlogging entry by shifting cultivators. Landings, cableways, skyline routes, and other poorly stocked areas left after logging have been filled successfully with *Paraserianthes falcataria* and *E. deglupta* (Tagudar 1979). These have been seen as a temporary pulpwood crop to be replaced naturally by dipterocarps. After 4-1/2 years, one planted area had an understory of 2,900 dipterocarp seedlings per hectare. Use of dipterocarp wildings to plant landings has been recommended as a practical technique in Sabah (Fox 1971).

Enrichment planting has proved of limited usefulness in tropical forests and generally has been abandoned (Stern and Roche 1974). Only in the dipterocarp forests of Peninsular Malaysia have the natural seedlings and saplings grown fast enough to supplement the prospective crop of the species planted. Tests with slower growing species and with slow removal of overhead shade led to repeated searching to relocate seedlings and interminable ground slashing, costing up to 10 days of work per hectare per treatment (Dawkins 1956, Mooney 1963).

An international questionnaire led to the conclusion that the failure of enrichment planting was also due to late or inadequate opening or the wrong choice of species (Fontaine 1976). Enrichment was no longer being practiced in west Africa by 1970 (Wood 1970).

Underplanting. Underplanting is distinguished from enrichment because it is not limited to the stocking of canopy gaps but rather is aimed at replacing the entire forest by planting a new crop beneath it. The term "line planting" is sometimes applied but is confusing because it is equally applicable to reforestation planting. Underplanting is intended to ensure full stocking, species control, crop uniformity, short rotations, and yields competitive with those of other land uses (Britwum 1976). Underplanting sets out trees in narrow, parallel corridors cut through the forest at a spacing that leads to full stocking as the planted trees approach maturity. It is intermediate in intensiveness between natural regeneration and reforestation planting and is most appropriate for countries with large areas of secondary forests (Wood 1976). It requires few trees, may save any natural regeneration present, and is usually less costly than complete plantations. Underplanting may also greatly increase prospective yields of secondary forests that would otherwise produce no more than 1 or 2 m^3/ha/yr (Earl 1975).

Underplanting apparently began in India and francophone Africa in the early 1930s (Catinot 1969a, 1969b; Laurie 1934a). By 1965, some 30,000 ha had been underplanted in Gabon and Ivory Coast. Extensive underplantings have also been made in what was formerly Zaire; smaller scale and experimental underplantings have been done in Brazil, Costa Rica, Ghana, Malaysia, Mexico, Nigeria, Puerto Rico, Suriname, Uganda, and Venezuela.

Underplanting with *T. superba* in French Equatorial Africa in 1938 was described as successful (Aubreville 1953). A small number of trees was planted per unit of area (12- by 12-m spacing), and a large percentage developed well. The need for similar tests in Cameroon and Ivory Coast was pointed out, with the suggestion that 23 tree species were worth trying (Aubreville 1947). Good results were predicted for *Swietenia macrophylla* in francophone Africa (Aubreville 1953).

Terminalia superba has also been underplanted in what was formerly Zaire (Wagemans 1958b). Tree spacing was 4 by 12 m or 8 by 12 m, and the stock planted was 2 to 3 m tall and stripped of leaves. At 8 years, the mean d.b.h. was 17 cm.

By 1961, underplanting of *Aucoumea* was being tested in Gabon (Biraud and Catinot 1961), and 130 ha of underplantings with *Aucoumea, Azfelia, Cedrela, Swietenia macrophylla,* and *Terminalia spp.* were established in what is now Malagasy (Bertrand 1961). By 1962, underplanting was the chief planting technique in Ivory Coast (Mensbruge 1962). Some 3.6 million trees had been planted, chiefly *Tarrietia utilis* and several Meliaceae. An area of 4,300 ha had been underplanted with *Senna siamea, G. arborea,* and other species (Mensbruge 1961).

By 1965, a wide variety of planting spacings and techniques were being used in the moist forests of francophone Africa (Catinot 1965). Spacings ranged from 4 to 6 m within strips and strip spacings ranged from 4 to 25 m. Typically, the strips were 3 m wide and 10 to 30 m apart (Catinot 1969a). The technique was described as easy, inexpensive, and protective of most of the ecosystem (Catinot 1974).

In west Africa, opening regularly spaced corridors destined to provide a full crop of planted trees required about 75 days of labor per hectare (Wholey 1955). Then, when light demanders such as *Aucoumea, Terminalia,* and *Triplochiton* were found to need nearly full light from the outset, less and less attention was given to retaining the natural forest. Retaining side shade had also been largely discontinued.

In Nigeria, tests with light demanders such as *Terminalia superba* failed. A common error was making the corridors too narrow. (They should be about 4 m wide.) It also proved necessary to release the corridors on both sides from the lower canopy and overhanging overstory. Some early failures were due to the use of undersized stock. (Plants should be at least 1.5 m tall.) Acceptable genera included *Chlorophora, Khaya, Lovoa, Swietenia, Terminalia, Terrietia,* and *Triplochiton.*

In Nigeria, Meliaceae striplings 1 m tall survived better than stumps and grew faster in height because they received more light. Running lines east and west to provide both early and late direct sunlight helped. Mortality and slow growth resulted from cutting only narrow lines through the undergrowth and not felling all overstory trees. Poisoning of overhead trees for at least 5 m on each side of the lines was needed.

Most underplanting in Nigeria was done from 1930 to 1962 (Oseni and Abayomi 1970). A shift to complete plantations followed because underplanted trees required more protection from animals and weeds than was considered justifiable.

After shelterwood proved unreliable in Ghana, underplanting became favored, even though it required protection from grazing animals, thorough ground preparation, and rapidly growing tree species (Danso 1966). By 1968, underplanting had become standardized; trees were planted 5 m apart in lines spaced 20 m (Osafo 1968b). The first year's work included demarcation, line cutting, canopy opening, cleaning, and planting. Line cleaning, "beating up" (replanting), and further canopy opening were done in the second year. Cleaning and opening continued for the next 3 years. Underplantings entailed rotations of up to 100 years. The best species were the African Meliaceae and *Tarrietia utilis,* the latter requiring full light from the outset. However, as logging roads were not maintained, the plantings became inaccessible and difficult to treat, so many failed.

In Papua New Guinea, clear felling and planting led to serious invasions of *Imperata* grass; therefore, felling intensity was reduced and *Araucaria hunsteinii* was underplanted, controlling the *Imperata* with the natural forest undergrowth (Godlee and White 1976).

Underplanting has been successful in the hill dipterocarp forests of Malaysia (Gill 1970). Spacing is 3 by 10 m, and both wildings and direct seeding have been used.

Observations of the regeneration of *Cedrela odorata* in Cuba led early to suggestions for underplanting (Roig 1946). The species apparently can withstand partial shade during its first years. As early as 1942, Holdridge (1942a) proposed that *Cedrela* be established in Puerto Rico at a density of about 12 trees per hectare among compatible neighbors.

In Suriname, underplanting has been tested (Vega 1977), with lines spaced 10 m apart. All undesirable trees 20 cm in d.b.h. or more were poisoned; repoisoning was done at 6 months if it was necessary. Promising species include *Aucoumea klaineana, C. angustifolia,* and *Cordia alliodora.*

Underplanted *Cedrelinga* trees at Tingo Maria, Peru, attained a height of 14 to 16 m at 6 years (Burgos 1955). Tests at Belterra, Brazil, along the Tapajos River also gave promising results after 4 years with *Bagassa guianensis, Carapa guianensis, Cordia goeldiana, Schefflera morototoni,* and *Swietenia macrophylla* (Yared and Carpanezzi 1981). *Enterolobium maximum* proved branchy, *Aspidosperma desmanthum* and *Genipa americana* grew slowly, and *Hymenaea courbaril* tended to lean. In Misiones, Argentina, underplanted *C. trichotoma* grew to 10 cm in d.b.h. and 8 m in height in 7 years (Cozzo 1969). Large openings (10 to 15 m) were necessary for this species.

An unusual technique was successfully applied in southern Queensland, Australia (Bevege and Richards 1970; Richards, B.N., 1961). On sites where *Araucaria cunninghamii* did not prosper because of poor soils, the species grew well when planted beneath 6-year-old plantations of *P. taeda.* This success was attributed to: (1) the role of N fixation, (2) the increased availability of N because of changes in the N cycle, and (3) reduced light intensity, improving the carbon (C)-to-N balance in the *Araucaria* where little soil N was available.

The French invested heavily in underplanting because they considered even close planting under shade superior to clear felling followed by reforestation (Lamb, A.F.A. 1966). This made it possible to retain the forest environment and to save pole-sized trees that otherwise would have been sacrificed. By 1970, two types of underplanting were being used in west Africa (Wood 1970). In one, all trees 30 cm or more in d.b.h. and the understory were removed, followed by planting light demanders, such as *Cedrela*. The other method recognized a need for initial shade for such species as *Entandrophragma utile;* therefore, the canopy was gradually removed after planting.

Reviews of underplanting experience have led to the following general recommendations for its use (Dawkins 1958c, 1961c; Foury 1956; White 1976a):

- Apply only where there is no prospective market for thinnings.
- Keep out fire and browsing animals.
- Leave no upper canopy.
- Plant as soon as possible after logging.
- Run lines east and west.
- Space lines 20 percent greater than final crown diameter to foster stand diversity between rows.
- Space trees within lines less than one-fifth of tree spacing between lines.
- Use only vigorous light demanders (such as gap species) that also tolerate intense root competition.
- Choose species that will grow 1.5 m/yr in height and self-prune from the outset.
- Plant stock 1 to 2 m tall.
- Reduce competition from overhead shade promptly and completely.
- Thin within lines for form and height, not for d.b.h. (except to favor trees much larger than the rest).

Few marketable tree species meet the growth-rate requirement specified here. In Africa, *Cedrela, Maesopsis,* and *Triplochiton* qualify. Many woods in prospective demand cannot be produced efficiently by this technique.

Underplanting has evolved to require large early openings and drastic cleanings for intolerant crops, removing nearly all of the former forest (Catinot 1969b). The canopy may be completely poisoned down to 30 cm in d.b.h., and the understory cut back as well (Wood 1970). In the Western Hemisphere, some of the canopy is left until trees such as *Cordia* and *Swietenia* develop before full release (fig. 5–2). In all cases, however, the former forest is greatly reduced.

Where accessible secondary forests abound, underplanting may be superior to either natural regeneration or field planting. It promises an immediate start on production with a small investment, even on some sites too poor for more intensive planting. Should pressures for shifting cultivation become overwhelming in the face of the long wait for a final harvest, intermediate products such as poles, pulpwood, or fuelwood might be harvestable from trees that survive or arise in association with the main agricultural crop.

Figure 5–2.—*Trees planted beneath openings in a forest canopy tend to develop straight boles.*

Group Planting. Group planting is a variant of underplanting. Groups of 9 to 25 seedlings are spaced 10 to 20 m apart. The trees are spaced about 1 m apart, usually in triangular arrangements (Ironside 1954). Group planting has not been used widely but shows promise in some places in west Africa (Catinot 1969b). The system has been used successfully in what was formerly Zaire (Dawkins 1955a). In Uganda, *Aucoumea, C. alliodora,* and *M. eminii* developed better in groups than in lines (Kriek 1968a). Dawkins (1958e) recommended groups of 13, 19, or 21 trees with the groups planted 30 to 60 cm apart, 75 to 125 groups per hectare. The central trees in a triangle tend to grow straight and free of weeds and climbers. In Suriname, groups containing only three trees, generally *A. klaineana, Cedrela angustifolia,* or *Cordia alliodora,* have been spaced 5 to 10 m apart. Tests in Brazil with *S. macrophylla* under high shade show some success in thwarting the shootborer problem. Generally, however, underplantings in lines provide more potential crop trees for selection than group plantings and may require less planting stock.

Forestation. Forestation relies solely on planted trees to develop a forest cover or a timber crop, either where no cover has existed before (afforestation) or where it has been removed (reforestation). Even where land clearing or other site preparation is not needed or is comparatively inexpensive, the initial investment required is sufficiently high to demand favorable terrain, soil quality, and accessibility—characteristics that may also eventually lead to great pressure for conflicting, marginal, agricultural uses. For sawtimber, the number of trees planted may be many times that of the final crop, the excess being thinned out and either sacrificed or harvested as intermediate products.

The potential for both productivity and risks is high in forestation. Usually, yields of good-quality, harvestable trees greatly exceed yields of alternative production systems. But failures have been common and often extensive because site limitations and the limits of adaptability of tree species (few of which are truly "native" to deforested and, particularly, degraded sites) were not recognized.

Plantation Composition

The species composition of a plantation is the primary key to its success or failure in terms of productivity, yield, and return on the investment.

Evaluating Tree Species. Forest planting has been done in every tropical country, and every country has searched for tree species as insuperable as teak seemed in India. Many failures convinced most foresters not to be coerced into undertaking large plantings in the Tropics without prior species testing (Lamb 1968a). The need for early testing is evident in Hawaii, a group of islands with few native tree species. Between 1921 and 1947 as many as 700 tree species were introduced, leading to the planting of nearly 10 million trees (Bryan 1947). Of these species, only 72 adapted well. Nevertheless, species selection continues to be somewhat arbitrary in spite of (or possibly because of) long experience and tradition. And the problem is exacerbated by a failure to communicate existing pertinent information to those who select the species. Much good information is now available in such excellent compendia as those of Streets (1962), Fenton and others (1977), Jacobs (1981), Francis (1984–Present), and Webb and others (1984).

Faulty species selection continues to cause many plantation failures in the Tropics because those making the selections do not take into account the intricate climate and soil patterns in mountainous regions and any site degradation caused by past cultivation practices, grazing, or fire. Careful species selection is important, however, because even among adapted species, selecting the best strains can double yields (Krishnaswamy 1957b).

Quoted yields of conifers and eucalypts generally include thinnings. Annual yields of 28 m^3/ha/yr (43 m^3/ha/yr on first-class sites) are commonplace. Even higher yields are reported from clones in Brazil. These contrast with a range of 14 to 21 m^2/ha/yr for other species, for which thinnings generally have little value.

Dawkins (1964a) points out that tropical yields exceeding 30 m^3/ha/yr generally occur at high altitudes or latitudes in areas with cool nights or a cool season. He speculates that respiration may be so rapid and continuous in the equatorial lowlands that the resultant photosynthate losses significantly reduce net productivity.

Whatever the causes of high productivity, it has been the chief criterion for selecting species for plantations, and selection is often made on the basis of early performance of trees planted at uncrowded spacings. A more comprehensive assessment is warranted. Odum (1969) points out that the more foresters select for succulence and growth, the more they must invest in chemical pest control, increasing the possibility of poisoning useful organisms, not to mention people and the environment. He asks: Why not practice the reverse strategy, selecting plants that are essentially unpalatable or that produce their own systemic insecticides while growing?

Bunting (1976) suggests that selection be made not on the basis of competitiveness but rather on commensalism (one organism benefits, the other is unharmed), mutualism (both organisms benefit), or compatability (the organisms "get along" with each other with little or no cost to either).

In the long run, the sustainability of different species in plantations will become a primary consideration. The importance of this is to be seen in the effects of different species on the nutrient reserves in the soil over a period of 18 years (table 5–10; Jorgensen and Wells 1986).

Schulz and Rodriguez (1966) conclude that the final decision on timber-species selection always rests on economic considerations. The acceptance of the product by industry and commerce is fundamental. Thus, tree species unknown to the trade, even if they have excellent silvical characteristics, may not merit selection for plantations.

Barnes and Mullin (1976) suggest that the productivity of plantations may be increased more by increasing the adaptability of accepted species through breeding and management than by seeking new species. Burley (1980b) described a logical sequence of selection: (1) matching species to the site through elimination trials; (2) selecting among possibles, a species-proving phase; and (3) genetically improving selected species.

Pure Versus Mixed Plantations. Simplicity has led to pure plantings of timber trees, and the pros and cons of monocultures versus polycultures, or mixtures, have been debated ever since. The advantages of mixed plantings were outlined by Laurie (1941c) and Wakeley (1954): (1) maintenance or improvement of site quality, (2) insurance against plantation destruction by a single agent (such as insects or fungi), (3) possible improvement of timber form (nurse crops), (4) comparison of species performance, (5) insurance against stagnation if thinning must be postponed, (6) insurance for a future seed source of the best of more than one species, and (7) possible higher value output by two or more compatible species. However, some of the support for mixtures is more emotional than intellectual. A mixture looks to be more in harmony with the natural vegetation of the moist Tropics; thus, there is a tendency to trust mixtures and question monocultures. Viewpoints presented abstractly and without support (Dickenson 1972) do little to clarify the issue. Nevertheless, the term monoculture has come to have almost an unsavory connotation. The reasons offered for this include: (1) the threat of excessive demand for certain soil nutrients, (2) the massing of food material and breeding environment for insects and fungi, (3) unbalanced return of nutrients to the soil, (4) questionable soil protection, and (5) little or no variety of food sources for bird life (Boyce 1954).

Table 5–10.—Effects of different tropical tree plantations on soil nutrient reserves over a period of 18 years

Site and species	Rotation (yr)	Nitrogen change (%)	Potassium change (%)
High-fertility soil			
Eucalyptus	3.0	−0.9	—[a]
Leucaena	4.5	+24.7	—[a]
Pinus	1.0	—[a]	−0.2
Low-fertility soil			
Eucalyptus	3.0	+9.5	—[a]
Leucaena	4.5	+213.0	—[a]
Pinus	1.0	—[a]	−7.5

Source: Jorgensen and Wells 1986.
[a]Not measured.

Florence (1967) predicted that a productivity decline is more probable in pure than in mixed forests because certain nutrients are more likely to become scarce where cycled according to the needs of but a single species. However, this effect may be buffered by the composition of leaf litter, which tends to reflect the nutrient content of the crowns.

Notwithstanding these concerns, in New Zealand, with its vast expanse of pure plantations of *P. radiata,* there are no reports of early prospects for planting any other species. Yet, responsible opinion favors developing alternative species to be available if ever needed (Anon. 1979a).

Based on experience in Ghana, Foggie (1957) concluded that pure timber plantations should be avoided except where such plantations are necessary for economic or other reasons and that a natural understory should be allowed to develop as soon as the main crop dominates the site. Nevertheless, Foggie does describe management complications using mixtures with different growth rates. *Terminalia* and *Triplochiton* grow four times as fast in height as African Meliaceae and form crowns much earlier; therefore, mixtures with the slower species prolong the tending period.

Experience in England suggests that the use of three or four species may be most productive, but it is a complicated practice (Darrah and Dodds 1967). Conifer/broadleaf mixtures are successful if the conifer outgrows the broadleaf and is salable early. Special planting patterns are suggested to accommodate differences in crown form.

An observation in Britain seems applicable to the degraded sites usually planted in the Tropics. Poor sites tend to restrict the choice of species and lead toward monocultures (Malcolm 1979).

Laurie (1941c) described a number of attempts at mixtures in India that apparently failed. Mixtures with teak led to poorer tree form than that obtained in pure stands. Even species that are complementary are not equal in value, so the better species would presumably be worth more alone. Mixing teak with *Pterocarpus marsupium* suppressed the teak. Mixing teak with *S. macrophylla* led to teak dominance on teak soils and *S. macrophylla* dominance on Latosols. Mixing *Gmelina arborea* and *Dipterocarpus turbinatus* resulted in *G. arborea* being so dominant that it had to be overthinned to bring through the *D. turbinatus.* Teak with a bamboo *(Melacanna)* understory was considered a possible crop combination.

An early statement regarding teak (Champion 1932) is still of interest:

> From the purely economic point of view, the value of teak timber is so much greater than that of any other species likely to be grown with it that relatively poor teak is almost always a sounder financial proposition than any other possible alternative. Expenditure is therefore justifiable to overcome the silvicultural difficulties if such really exist.

In support of mixtures, it has been noted that even though a species may grow pure in nature, this is no indicator that it should be grown that way commercially (Peace 1957). The lack of competitors on its natural site may be due to causes independent of species preference.

An almost universal problem with species mixtures is their maintenance. Differences in growth rates lead to dominance by one species, with the others falling progressively further behind (Anon. 1952g, White 1976a).

An example involving two rapidly growing trees in the Philippines illustrates some of the difficulties in managing mixtures (Zabala 1975). The two species used, *Paraserianthes falcataria* and *Anthocephalus chinensis,* were planted at 2 by 2 m. After 5-1/2 years, the *Paraserianthes* was larger in d.b.h. and volume than in a monoculture, whereas the *Anthocephalus* was smaller. The *Paraserianthes* suppressed the *Anthocephalus* and apparently took its space.

Experience in Puerto Rico further exemplifies the difficulties of managing species mixtures. Two or more species initially thought compatible seldom prove to be. If one outgrows the other, the slower must either be preserved at a sacrifice in productivity or sacrificed at the expense of the mixture. Mixing a rapidly growing intolerant and a more slowly growing intolerant may solve the problem of compatibility, but it leads to two rotations, with the later crop subject to felling damage from the first and probably lower growth rates for both.

What has been said here appears mostly to be in defense of pure plantations, but there should be no objection to an understory of species different from the main crop, except where it might create a serious fire hazard. Such an understory might be (and generally is) of mixed native species.

Pure plantations, even of teak, have been criticized from the very outset, notwithstanding an early conclusion that called the "problem" of the pure teak plantation a false alarm if good sites and good strains of the species are used (Laurie and Griffith 1937). A favorite rejoinder to those favoring monocultures is "Saxon spruce sickness," referring to a progression of worsening crops beneath successive pure spruce plantations in Germany on a site formerly covered by a mixed broadleaf forest (Smith 1962). However, exhaustive study has shown the phenomenon resulted from planting the wrong tree species on the site rather than from the purity of the plantation *per se*.

Encouraging diversity for its own sake, on the other hand, may not improve ecosystem stability (Murdoch, cited by Clarke 1976). The crucial variable is not simply the number of species but rather the species themselves and the interactions among them.

Early observations in pure teak plantations in India did not support the serious concern then expressed (Kadambi 1945). No growth decline took place. The undergrowth beneath well-managed stands appeared to control erosion. Fluting of teak boles was no worse than in natural forests, nor was damage from insects. And the timber sold at the same price as old-growth teak.

A study of the nutrient content of litter in Brazil provided no evidence that monocultures per se lead to more rapid depletion of soil-nutrient reserves than do mixtures, other things being equal (Chijioke 1980). Rapid nutrient depletion is clearly associated with rapid growth, short rotations, and whole crop harvesting; but further study is needed to show whether a single crop immobilizes nutrients faster than does a mixed crop.

Yields. Widespread pure planting would not have taken place or continued unless there were also arguments in its favor. A classic statement by Champion (1933) describes the position that led to large areas of pure teak plantations in southern and southeastern Asia:

> Even more than in Europe single species tend so greatly to outdistance all their associates from an economic point of view that a crop quality inferiority of even two quality classes as compared with potentialities with the associates is insufficient to equalize returns from the first rotation if financial prospects alone are considered. Since no drop in soil quality has ever been demonstrated it is unlikely that the formation of mixtures will improve soil conditions by more than a fraction of a quality class, much less two. Such little improvement as can be expected from a mixture is likely to be almost as well provided by maintenance of a good natural mixed undergrowth. More investigations are required on this point, but it appears that the formation of mixtures for the maintenance or improvement of site quality is unlikely to be worth while.

The famed Changa Manga plantations in Pakistan are mixtures of various tree species destined primarily for fuelwood. When an Australian visitor saw the possibility to double the yields by planting *Eucalyptus* (Pryor 1968a), he specifically recommended against mixing the *Eucalyptus* with *Dalbergia* and *Mora*, the species planted hitherto. Instead, he recommended testing three species of *Eucalyptus* and then presumably choosing the species that was best suited for each site.

The prospect of mixed-crop production "overyielding" (that is, exceeding the yield of any crop alone) is one of the attractions of species mixtures. Financially, such a result must be extremely rare. In physical terms, mixed yields of 572 grasses and grains usually fell somewhere between the monoculture yield of the best and poorest components (Trenbath 1974). Relative yields approached unity; that is, what one species gained, the other lost. In the few cases where mixed yield surpassed that of each component in monoculture, it was not clear whether the results were repeatable.

An interesting example of overyielding among forest trees was found in Hawaii (DeBell and others 1985). *Eucalyptus* was grown with leguminous trees in alternate rows at a spacing of 2 by 2 m. Not only were the eucalypts in the mixtures larger than those in pure stands at 65 months, but the mixed stands also produced 1.4 to 2.5 times as much dry wood fiber as the eucalypts alone (table 5–11). Nutrient levels in the *Eucalyptus* in the mixed plantations suggested a contribution from the leguminous trees. Similar findings were reported in the northwestern United States for a 27-year-old stand of *Pseudotsuga* grown with and without an understory of Alnus, an N fixer (Tarrant 1961). The N content of the

Table 5–11.—Overyielding of *Eucalyptus* planted with leguminous trees in Hawaii

Plantation type	Results at 65 months D.b.h. (cm)	Height (m)	Dry weight (t/ha/yr)
Pure *Eucalyptus saligna*	9.5	11.6	6.9
Mixed			
Eucalyptus	12.1	14.9	6.5
Acacia melanoxylon	9.3	11.3	3.0
Total			**9.5**
Mixed			
Eucalyptus	15.3	19.0	10.7
Paraserianthes falcataria	14.6	18.1	6.8
Total			**17.5**

Source: DeBelle and others 1985.

Note: Overyielding is defined as exceeding the yield of *Eucalyptus* planted without leguminous trees.

Pseudotsuga foliage and of the soil was significantly higher with the *Alnus*. After age 20, the *Pseudotsuga* in mixed stands was also growing more rapidly.

Laurie (1941c) hailed mixtures as a protection against insect attacks, arguing that separating the tree species would slow the spread of the pests. However, in close plantings of few species, such protection may be negligible. Moreover, he cited no evidence where dilution of the crop by mixture significantly affected the incidence of insect attacks or diseases. Nevertheless, mixed undergrowth is a good habitat for the parasites and predators of insect pests.

Shootborer attacks by *Hypsipyla* spp. have led to abandonment of *Cedrela* as a pure crop in much of tropical America. Mixed plantings were proposed long ago (Andrade 1957) and in some areas have reduced (but not eliminated) shootborer attacks. The discovery that the insects have a limited flight radius tends to explain the reduction (Grijpma 1976).

A summary of experience with forest monocultures concluded that the system has led directly to an increase in the number and severity of pests and diseases of forest crops (Gibson and Jones 1977). Effects of diseases have been greatest in the nursery and early plantation stages. But much of this increase is attributed to the uniform and crowded conditions in plantations and to the cultural operations that have often exacerbated other problems.

The most pessimistic forecasts of the dangers arising from forest monocultures are thought by some to be fully vindicated (Gibson and Jones 1977). However, few of the most disastrous outbreaks of forest pests and diseases in the Tropics can be attributed to monoculture systems. Foresters have avoided pest problems by strategic choice of species. The economy of intensive plantations allows for expenditures for protection. Moreover, the compact nature of intensively managed plantations benefits pest control (Gibson and Jones 1977).

Peace (1957) cites the example of the fungus *Armillaria mellea*. If it attacks a pure stand, the damage is serious. In a mixed stand, the attack is less devastating only if one or more of the components is resistant. Of course, if all the trees were of the resistant species (leading toward purity), the attack would have least impact. Stated in another way, if there are two or even five species in a mixture, trees of each would still be close enough so that all of any species might suffer just as heavily from an insect attack or disease as it would grown as a pure stand. If only one species of the mixture is susceptible, an epidemic would be only one-half or one-fifth as damaging as if all the trees of a pure plantation were the susceptible species. By the same token, however, the probability of an epidemic occurring to a single species in a pure plantation should be only one-half to one-fifth as great as where two to five species are exposed. Theoretically, at least, the risks may be about the same. The warnings of theorists about monoculture susceptibility to pest and disease risks have been supported by only a few examples in the Tropics, Rosayro (1954) noted, and his statement apparently is still valid.

Recent planting of *Leucaena leucocephala* in pure stands in the Asia-Pacific region encountered an insect defoliator termed the leucaena psyllid *(Heteropsylla cubana)* (van den Beldt and Napompeth 1992). First reports described a sudden and dramatic dieback of the leucaena. By the second year the pest population had peaked. By the third year the pest was largely absent. Even highly susceptible varieties of leucaena survived in infested areas. Resistance may have resulted in part because of the existence of resistant varieties in the vicinity.

Native Versus Exotic Species. Of the thousands of tree species that grow in natural tropical forests, many are sufficiently valuable to justify harvesting for human use. So what better source of trees for future crops might be expected than that of the native forests? Is there not also a danger that exotics might wipe out natives? Such reasoning has produced strong support for the use of native species wherever possible (Parker 1940).

The term "exotic" is not generally used in any ecological sense, because it commonly refers to political rather than natural boundaries. For example, some species from what is now Myanmar became "exotic" to India when the two countries were separated in 1937. Are not coastal species equally "exotic" to the uplands of the same country? Likewise, the term "native" may not be very meaningful. Although a species native to an area may be better adapted to it than a nonnative, the site being planted is seldom the same as where the "native" species grew in nature. The important question is whether the species is "native" or "exotic" to a site that may long have been cleared and repeatedly burned, cultivated, or grazed. These changes may be so drastic that species not found in the former native forest may now prove best adapted there. Broad capability of adaptation to such conditions characterizes eucalypts and pines and explains their popularity in the Tropics. Prospective performance is more important than origin in selecting species to plant. Arbitrarily rejecting exotics excludes many species that merely never had an opportunity to migrate to the site and do not lack adaptability thereto.

To be successful, an exotic timber tree must be: (1) able to better serve a particular purpose than available local species; (2) suited to the local climate and soil; (3) easy to grow and regenerate; and (4) resistant to local hazards, such as fire, insects, diseases, and grazing (Laurie 1941f). These seem to be stiff requirements, and it is reasonable to question how any exotic tree could outperform natives in such respects. Nevertheless, some promising exotics have extraordinary vigor and growth rates. Rejecting the theory that aliens are inherently more aggressive because they are alien, Egler (1942) pointed out that in Hawaii exotics seem to succeed because the local environment has been altered by humans. He concluded that if human influences were removed, the advantages to outsiders would diminish.

The introduction of exotics may be doomed to failure if they do not come from a similar environment or may, at the other extreme, lead to unwanted escape and "naturalization." Even the most carefully selected exotic species need testing for site adaptability and performance while planting is kept to a small scale.

Early species introductions usually were based on imprecise information as to the requirements and usefulness of the species and sometimes even their identity. By 1960, 837 tree species were introduced into Hawaii (Nelson 1965). More than 10,000 trees of each of 80 different species were planted. Of 16 species from tropical America, 1,290,000 trees were planted; few proved promising.

Early plantation testing in tropical America led to more use of native species. Gonggryp (1948), after establishing a remarkable set of early planting tests in Suriname, recommended further study with *Bertholletia, Carapa, Caryocar, Eperua, Goupia, Hymenaea, Manilkara, Mora, Schefflera, Triplaris, Virola,* and several native Lauraceae.

From Brazil also came early proposals to make the most of the native forest flora (Klein 1966, Pitt 1966, Wasjutin 1951). It was concluded that substituting foreign species for the local flora would result in disharmony among the soil, flora, and fauna of the region. Lists of pioneer species suggested for trial plantings, by genera, included *Andira, Araucaria, Aspidospermum, Balfouradendron, Buchenavia, Calophyllum, Cedrela, Chlorophora, Colubrina, Copaifera, Cordia, Hieronyma, Jacaranda, Lonchocarpus, Manilkara, Myriocarpus, Ormosia, Piptadenia, Tabebuia,* and *Xylopia.*

In India, numerous native species outgrow exotics (Qureshi 1968a). Genera with species reportedly capable of exceeding 10 m^3/ha/yr include *Anthocephalus, Artocarpus, Gmelina, Lophopetalum, Michelia, Terminalia,* and *Toona* (fig. 5–3).

In addition to the timber species known to produce useful woods, there are many more tree species that are sparingly used, even within their natural ranges. Such species include *Acacia albida* (for feed and protein), *Brosimum alicastrum* (for feed and protein), *Caryocar brasiliensis* (for oil), *Gulielma utilis* (for oil), *Orbignya martiana* (for oil), *Prosopis tamarugo* (for feed and protein), and *Simmondsia chinensis* (for wax and oil) (McKell 1981). These species thrive under adverse conditions and apparently do so because they are native.

Early planting tests in the wet Pacific region of Colombia (300 to 440 cm of rainfall annually) indicate that some

Figure 5–3.—*Avoidance of costly weed control has led to the selection for planting of tree species of very rapid early growth, as illustrated by this first year development of* Anthocephalus chinensis.

native species may do better than exotics there (Peck 1976a). *Anthocephalus chinensis* was rejected because of poor form. *Cedrela* spp., *Cordia alliodora, J. copaia, Ochroma lagopus,* and *Zanthoxylum tachudo* showed promise.

Exotics were not introduced into what is now Malaysia, especially well endowed with native species, until later than most other countries. As late as 1953, Barnard (1953) wrote that the timber quality, stem form, and growth rate of many indigenous tree species left little to be desired. He concluded that exotics would need to be outstanding in timber quality, growth rate, and ease of establishment to be introduced in place of indigenous species for which natural regeneration could successfully and economically be established.

With the growing population of the Tropics and resultant increased local demand for utility woods, markets for an increasing number of native tree species have developed. Nevertheless, local shortages promise to worsen. This prospect has shifted attention from quality to quantity timber production. Despite the presumed advantages of native species, the need for increased yields has forced their reassessment. Indeed, in spite of the current promotion of native species, experience in timber production throughout the Tropics has led to an almost universal preference for exotics. For example, although some 450 native tree species had been test-planted in India by 1937 (Sen Gupta 1937), exotics have been much more widely used. Exotics are particularly popular for pulpwood production on the worst sites, such as coastal sands, dunes, swamps, and degraded soils where the native forests were a low-grade mixture of little commercial value (Chaudhuri 1952).

It was apparent early that India's needs for construction timber required more rapid production than was possible with many indigenous tree species (Sahni 1965). In the dry regions especially, the native species grow too slowly (Kaul and Nambiar 1966). In addition, most native timbers are heavy, hard, and difficult to season. Therefore, from 1958 to 1966, a total of 277 species of trees and shrubs was introduced in Jodhpur for fuel and livestock feed. About 15 were found promising, including 8 species of *Eucalyptus*.

In India, a 15-year-old exotic plantation of *E. camaldulensis* accumulated more organic matter than a 55-year-old, mixed, native *Shorea robusta* forest (Jha and Pande 1984). The physical soil properties were also better under the *Eucalyptus* than the *Shorea*. The *Eucalyptus* raised the soil pH and the *Shorea* lowered it.

The greater fire resistance of some exotic species led to their introduction into African savannas (Adekunle 1965). On the northern grasslands of southern Cameroon and on the Nigerian savannas, eucalypts and pines were found to resist fires and produce much more fuel than native trees.

In Nigeria, the need for pitprops at Enugu led to plantations of the native *Nauclea*. But as these failed, the exotic *Gmelina* was substituted and proved successful (Foote 1953). In South Africa, 15 indigenous species were tested from 1912 to 1927; none produced adequate yields (Pudden 1957a). *Juniperus procera* (East African pencil cedar) was planted on a large scale, whereas *Ocotea usambarensis* (camphorwood) was found adapted only to high elevations. Meanwhile, plantations of *Eucalyptus* had, since 1910, proved productive of fuelwood for railroad use. Tests of 48 conifers showed three species of *Cupressus* and two of *Pinus (P. patula* and *P. radiata)* to be promising. Tests of 150 broadleaf trees, including 70 eucalypts, showed *E. saligna* and *E. globulus* to be especially well adapted (fig. 5–4).

On the savannas in Nigeria, indigenous species planted for fuelwood compared unfavorably with those from India, such as *Azadirachta indica, Senna siamea,* and *Dalbergia sissoo* (Page 1948). No Nigerian savanna

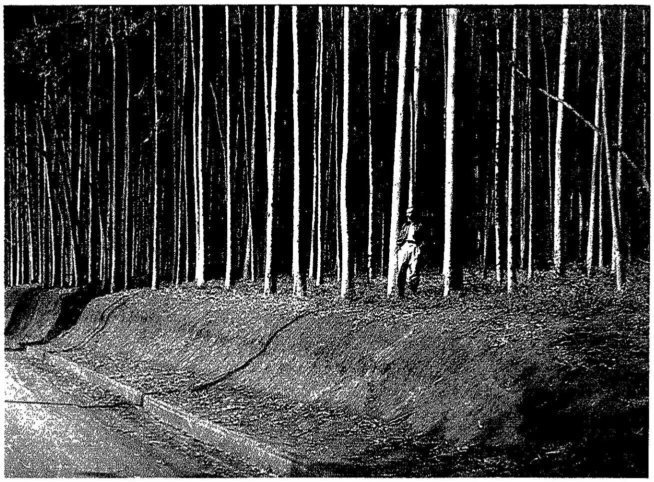

Figure 5–4.—*Eucalypts have been selected widely in tropical America because of their rapid growth and adaptability to degraded soils.*

species grows more than about 2 m in height per year, and most grow much more slowly. However, native African species such as *Daniellia oliveri, Khaya senegalensis,* and *Prosopis africana* struggle through grass and scrub growth in their young stages and withstand some fire damage, which the Asian species could not.

In the dry areas of the Sudan, the only indigenous genera that have produced merchantable timber are *Juniperus* and *Podocarpus,* and both require 150 years to reach maturity (Jackson 1960). On the other hand, exotics such as neem *(Azadirachta)* and *S. siamea* were considered very promising for fuelwood. Similarly, in Ivory Coast, the native species were found to be slow growing, leading to the introduction of exotics (Mensbruge 1968).

By 1957, 110 exotic timber tree species were being tested in what is now Malawi (Willan and McQueen 1959). In 1960, the main trees being used in Uganda were American species, *Cupressus benthami, C. lindleyii, Pinus caribaea,* and *P. patula* (Leuchars 1960). Also being tested were other pines and *Abies religiosa,* also from America. At about the same time, 18 American species were being tested at the Maguga Arboretum, Kenya, including (in addition to those just mentioned) *Araucaria angustifolia, Cedrela odorata, Fraxinus berlanderiana, P. ayacahuite, P. engelmannii, P. leiophylla, P. montezumae, P. occidentalis, P. oocarpa,* and *Prunus salasii* (Howland and Griffith 1962).

In Fiji, indigenous timber species, including the most widespread native conifer, *Agathis vitiensis,* were also found to grow slowly (Cottle 1957, Loweth 1953). Among native species, only *Endospermum macrophyllum* shows promise for plantations; its soft wood is usable chiefly for construction and boxes. Meanwhile, 74 species of greater promise were introduced.

In Suriname, 30 native species were tried, including large plantations of *Carapa* and *Hura;* the conclusion was that generally they do not warrant extensive planting (Schulz and Rodriguez 1966). Growth of these species was slow and tree form was poor. Two exceptions were *Simaruba amara* and *V. surinamensis.* Puerto Rico has had a similar experience, even though more than 100 potential native timber candidates were tested (Wadsworth and Schubert 1977).

Wright (1976) suggests the following reasons natives tend to fare worse than exotics:

- Selection in nature favors survival more than economic traits.
- Evolutionary response lags behind environmental changes.
- Human-caused changes do not produce evolutionary responses.
- Evolutionary possibilities in native flora are limited.
- Native species may be decimated by introduced pests.
- Native species tend to be sensitive to planting shock.
- Natural species distribution may be limited by factors unrelated to performance.

A 1966 survey of trials of rapidly growing trees in tropical countries in the British Commonwealth showed that of 19 "probable species," 3 were from America, *C. odorata, Cordia alliodora,* and *Swietenia macrophylla* (Pitt 1966). Of 28 "possibles," *Araucaria angustifolia, Enterolobium cyclocarpum,* and *Simarouba amara* were from America. Low-density species from America included the following genera: *Bombax, Cecropia, Ceiba, Jacaranda, Ochroma,* and *Trema.*

Wood (1974) pointed out that the area of high forests economically "renewable" under sustained yield in tropical countries is small because the extensive tending and long rotations that were practical in the past are now of questionable feasibility. He concluded that except for a few species, such as those of *Terminalia* in west Africa, *Maesopsis* in Uganda, *Cordia* and *Hibiscus* in the Caribbean, and *Tectona grandis* in southern and southeastern Asia, indigenous trees grow too slowly, a drawback that only forest-rich countries can afford. Thus, long-term planning must not exclude exotic species from planting proposals.

The high productivity of eucalypts grown as exotics has been ascribed in part to higher nutrient levels (particularly N and P) abroad than in their native Australia (Pryor 1968a). Escape from the insects of the native environment has also been considered partly responsible. Jacobs (1956) explained that savanna species of eucalypts grow much faster in suitable localities outside Australia than within the country, provided the leaf-eating insects that have evolved with the genus in Australia are not also introduced. Jacobs advised foresters abroad to pay as much attention to the strain of the species introduced from Australia as to the species itself. Expenditures for strain selection and collection from elite trees (verified by testing as being of superior genotypes) within the strain are likely to prove rewarding. He further pointed out that the more rapid growth of the trees overseas may be accompanied by poorer wood quality than is obtained in Australia because growth stresses have not had time to subside. Longer rotations should reduce growth stress.

Baker (1970a) also asserted that the best reason for growing commercial plants outside their native habitat is separation from diseases and pests that have evolved along with them. An analysis of the diseases of *Pinus caribaea* in its native range between 300 and 900 m in elevation in what is now Belize indicated that geographic factors limiting the distribution of these diseases minimize any threat to this tree as an exotic (Etheridge 1968). Among the diseases mentioned are dwarf mistletoe, true mistletoe, needletop necrosis, and progressive dieback.

Species Selection

Champion and Brasnett (1957) pointed out that foresters choosing species to plant on a given site or selecting sites and species for the production of a particular kind of timber need to know about local climates and plant associations so they can explore other similar sites for additional species. If it appears appropriate to test exotic species, foresters will obviously first consider making introductions from homoclimes.

The planting of *P. caribaea* in Misiones, Argentina, showed how taking a species well beyond its natural range can affect productivity (Larguia 1967). At age 6, only 4 percent of the trees had good enough form for future timber. Many were too crooked even for pulpwood. Other defects included excessive foxtail (resulting in storm breakage) and spiral grain.

Where climatic matching has been successful and the source is distant, the time lag for pests and diseases to follow introduced species may be long. As an example, *P. radiata* from California was planted in Australia in about 1877 (Thomas 1957). A dieback was observed 5 years later but caused no concern for more than 30 years, after which planting was suspended for 3 to 4 years. Thereafter, planting continued until 1957, when 38,000 ha were planted. A zinc (Zn) deficiency diagnosed in 1940 was correctable. Browntop was also discovered but could be reduced by adding N and superphosphate. Similarly, the eucalypts brought to Brazil from Australia early in this century, although not entirely disease free, are not yet plagued by the leaf-eating insects common to their native environment. Even if this were to happen, as well it might, few foresters would regret the years of high-performance plantations, and the investment involved should support the research necessary to either solve the problems or develop alternatives.

The ecology of exotics itself seems to arouse interest in their testing. Factors limiting natural distribution are not purely a reflection of species adaptability to climate and soil. Factors responsible for the natural range of a species (Good 1953) usually include: (1) place and time of origin, (2) distribution of climatic limits, (3) distribution of edaphic limits, (4) potential for dispersal, (5) configuration of land and sea, and (6) influences exerted by other plants (direct competition and indirect effects). If the influence of any one of these factors is sufficiently adverse, a species could be excluded from an area where it might otherwise be successfully introduced.

In the exotic plantations of New Zealand, maximum yield is not necessarily obtained only under conditions identical to the species' natural habitat (Jackson 1965). A clear distinction must be made between the ecological and physiological limits of productivity. The importance of this distinction will increase as management intensifies.

When the disease susceptibility of natives and exotics is compared, both must be planted at similar spacings (Harper 1977). It is not valid to compare disease incidence in pure plantings of exotic species with that in widely spaced, uneven-sized, natural stands of native species. Native species, when planted at the same time and spacing, may develop some of the same problems as exotics.

Characteristics To Consider. Two compilations of significant factors in species selection (Fenton and others 1977, Webb and others 1984), taken together, include the following:

- Nomenclature—Preferred scientific name; botanical family; variety, race, or provenance; local and trade names; other scientific names in use

- Natural occurrence—Geographic units, latitude range, altitude range

- Where in use—Managed natural forests versus plantations
  - — Site tolerances—Annual rainfall, rainy period, length of dry season, mean temperature, mean temperature of hottest month, mean temperature of coldest month, light requirement, soil texture, reaction, drainage, salinity
  - — The tree—Size, description, form, utility of wood, utility of other products, utility for nonwood purposes, protective value, ornamental value
  - — The wood—Density, natural durability, preservation, facility of sawing, seasoning, other features
  - — Regeneration—Natural regeneration, seed sources, reproductive phenology, seed weight, seed storage, seed pretreatment, germination rate, germination percentage, direct seeding, coppicing capacity, tree improvement in progress, planting stock, spacing, light requirements, water requirements, shade tolerance, need for root pruning, lifting size, production time, containers, other nursery needs

- Plantation management—Weeding, pruning, thinning

- Yields—Mean annual increment by age.

Information in these categories is presented for many promising tree species in appendix F.

In their classic treatise on the choice of tree species, Champion and Brasnett (1958) focused on the following factors: water requirements, temperature requirements, topographical requirements, light requirements, susceptibility to damage from physical agents and biotic factors, and known extension outside natural range. Other studies (Barnes and Mullin 1976, Jacobs 1981, Moni 1965) have emphasized some additional characteristics: freedom from need for presowing seed treatment, natural regeneration propensity, capacity to colonize bare ground, vigorous root system, resistance to drought and wind damage, capacity for rapid growth, performance as a plantation tree, short rotation length, durability of timber, and versatility of wood. For underplanting, Wood (1974) emphasized the need for species that not only undergo rapid initial growth but also close a canopy quickly, such as those in the genera *Cedrela, Gmelina,* and *Terminalia* do in Africa. Evans (1992) lists characteristics that are helpful in classifying tree species for different end uses (table 5–12).

A wide natural range indicates broad adaptability in tree species (Sahni 1965). *Eucalyptus camaldulensis* is a good example, because it is found in nearly every state in Australia. A notable exception to this rule is *P. radiata,* which is restricted to a small natural range in western North America yet has adapted to a much larger area in the Southern Hemisphere.

The outstanding success of planted eucalypts is attributable to a number of exceptional characteristics of this genus and its nearly 700 species and varieties (Cromer 1956). They are adapted to a wide variety of climates and soils, ranging in latitude from 10° to 43° and in altitude from sea level to 2,100 m. Most withstand fire, regenerate easily from seeds or coppices, and self-prune readily. A wide range of wood properties is also found within the genus; eucalypts make excellent firewood, they are capable of exceptionally high yields, they thrive where there is periodic drought (Pryor 1968), they grow well outside their area of origin, they are highly productive on short rotations and close spacing does not hinder growth, they respond to fertilizer better than conifers, and the large number of species and provenances promises great genetic gains through selection and hybridization. One significant drawback is the high density of

Table 5–12.—Timber production and property requirements by end use

End use	Production requirements	Property requirements
Fuel	Rapid growth, early culmination, easy to grow, economical, coppicing desirable	Quick drying, low ash content, readily burnable with no odor
Pulp	Same as above, but with straight stems	Fiber length, light color, low extractives, papermaking quality
Solid products	Large size, moderate to rapid growth, good form, ease of pruning, freedom from buttrot	Strength, stability, uniformity, good seasoning, working and finishing
Sheet products	Very large size, good natural pruning, rapid occlusion	Figure, peeling or slicing quality, good bonding

Source: Evans 1992.

most species, making sawing and seasoning the wood difficult.

The attributes of *P. caribaea* (Lamb 1973) that make it favorable for planting include ease of seed collection, duration of seeds in storage, ease of germination, rapid early growth, adaptation to degraded sites, adaptation to shallow soils, fine branches, wind resistance, relative freedom from diseases, wide natural variation permitting genetic selection, ease of form improvement in one generation, ease of hybridization, pulpwood quality, and quality of resin. Drawbacks include poor seed crops where winters are moist, lack of frost tolerance, need for container planting, lack of competitiveness with climbers, presence of compression wood in young crooked trees, and weakness of the central wood core of rapidly growing trees.

The foxtailing (terminal hypertrophy) of pines may be an indicator of both adaptability and productivity (Kozlowski and Greathouse 1970, Lanner 1966). Foxtails are pines that do not stop growing, make no rings, and produce no lateral buds until eventually, after a long stem has formed, moisture stress slows growth and terminates the phenomenon (fig. 5–5). Some 12 species are reported to produce foxtails, including *P. caribaea, P. kesiya, P. merkusii, P. oocarpa,* and *P. tropicalis.* Within Belize, the home range of *P. caribaea,* foxtailing occurs on 1 to 2 percent of the trees, with a tendency to increase with elevation and fertility (Abell 1969). Foxtailing is said to be strongly inherited (Kozlowski and Greathouse 1970), but there is also marked climatic influence. In the uniformly moist climate of Misiones, Argentina, 80 percent of the pines are foxtails (Lanner 1972). Foxtailing has been reduced in Australia by strategic selection of phenotypes and progeny.

Other potential coniferous genera for the Tropics are listed in appendix G (Weck 1963).

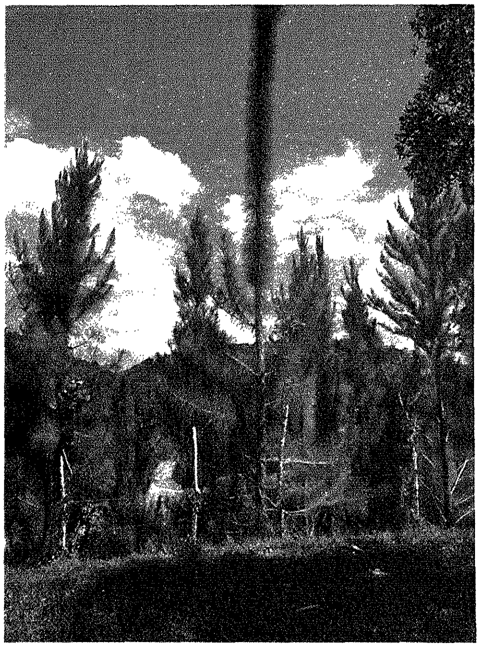

Figure 5–5.—*Pine foxtails, although characteristic of vigorous, fast-growing trees, are generally perceived as abnormal and eliminated in early thinning.*

Nitrogen-fixing species might appear to be superior on poor soils. For example, a 13-year-old plantation of *Casuarina equisetifolia* on a sand dune in the Cape Verde Islands (Dommergues 1963) produced 58 kg/ha of N per year. However, about the same accretion of N, 50 kg/ha/yr, has been found in plantations of *P. radiata* in Australia; this is two to three times what might be expected of a species not considered an N-fixer (Richards 1964). For this amount of N to be produced, other known fixation agents would have to be greatly stimulated. Whatever the process, this characteristic makes pines even more desirable than other species in tropical areas.

Golfari (1961, 1968a, 1981) has found details of climate to be highly significant in determining the adaptability of coniferous species in South America. In addition to the mean temperature, the forester should consider monthly temperature means, temperature extremes, the distribution of precipitation, relative humidity, and illumination. Likewise, the soil texture, pH, porosity, and depth to water table will affect species suitability. Golfari classifies species by their adaptation to winter or summer rainfall, moisture deficit, and temperature difference between winter and summer, and their thermal efficiency (*P. patula,* cool; *P. caribaea,* warm) and minimum limiting temperature (degree of frost resistance). He uses survival and the rate of height growth as measures of adaptability.

Golfari (1963) concluded that all conifers fall into one of three major groups regarding adaptation to rainfall distribution, those requiring: (1) moisture mostly in the winter and capable of withstanding summer drought, (2) moisture uniformly distributed throughout the year, and (3) moisture in the summer and capable of withstanding dry winters. These three rainfall patterns were recognized as significant to vegetation some 30 years earlier (Troup 1932).

Golfari (1978a) and Golfari and others (1978) derived further guidance in tree selection from the performance of different species already established on a variety of sites. Their conclusions, which follow, should apply universally:

- Early height growth is a good indicator of adaptation of species to a site.

- Uniform growth of individual trees denotes favorable conditions.

- Self-pruning is a sign of a favorable site.

- Susceptibility to insects and diseases is minimal on sites to which trees are well adapted.

- Water deficit (derived after Thornthwaite and Hare 1955) is of great importance in identifying homoclimes.

The significance of winter/summer rainfall to species adaptability is reported to be similar for *Eucalyptus* (Pryor 1972b). Trials of *Eucalyptus* offsite show that species from winter rainfall zones fail in summer rainfall zones, although the reverse is not true. Species in the monocalyptus (a taxonomic subgroup including the stringybarks, ashes, and peppermints) group, including the major timber-producing *Eucalyptus* species of Australia, are less apt to adapt elsewhere than others. Species known to be naturally limited by fire can, if protected from fire, be extended into sites adjoining where they occur naturally.

Tree productivity per unit of area is related to crown shape (Ashton 1978a). Many-layered crowns with single, central stems produce more per unit of area than broadly hemispherical, multistemmed, single-layered crowns. This finding confirms Dawkins' (1964a) recognition of the advantage of trees that grow well with a small crown-diameter-to-d.b.h. ratio. This advantage (seen by both Ashton and Dawkins to be affected by tree age) also differs among species. Dawkins (1964a) notes that all high-yielding conifers and eucalypts are small crowned, with crown-diameter-to-d.b.h. ratios less than 15, and less than 10 in *E. saligna.*

Characteristics of no silvicultural significance may dictate species preference. In the Brazilian states from Sao Paulo to Rio Grande do Sul, most recent plantations are coniferous, whereas in Minas Gerais and Espiritu Santo, eucalypts have chiefly been used (Golfari 1970b). The state of Sao Paulo has been the most heavily planted with eucalypts in the past, but they have been found to be inferior to pines for paper because their wood is dark and requires more bleaching. Also, the sawmills in Brazil are not yet accepting much *Eucalyptus* wood. A change in this trend is foreseen, as happened in Australia (Golfari 1975b).

Currently, eucalypts and pines are the species most commonly used in tropical timber plantations (Evans 1992); together, they account for 72 percent of all plantation area (table 5–13).

Table 5–13.—Species composition of tropical timber plantations

Species group	Percentage of plantation area
Eucalyptus spp.	38
Pinus spp.	34
Tectona grandis	14
Other nonconiferous spp.	11
Other coniferous spp.	3
Total	**100**

Source: Evans 1992.

Preplanting Site Analysis. The numerous spectacular examples of highly productive plantations of either native or exotic timber tree species have resulted either from "luck" (sometimes a euphemism for expensive trial-and-error) or, less commonly, from carefully analyzed matching of species tolerances to site conditions. Usually, an extensive, time-consuming period of trials involving not only many species but also their varieties and provenances (seed sources) is required (Baur 1964a).

Even within the limits of individual planting areas, sites may vary enough to call for a variety of tree species. And even within large genera such as *Eucalyptus,* judicious selection of species and provenances may be critical. Selections are usually based on natural ranges and corresponding climatic limits or on proved adaptability to altered environments (Cromer 1956).

The results of broadscale species trials are highlighted by experience in Puerto Rico (Wadsworth and Schubert 1977). Of more than 400 tree species introduced there since 1922, only 25 are currently in use or show promise for timber production. Between 1924 and 1946, 9,000 ha of public forest lands were planted with 131 tree species, but these plantations were only 60 percent stocked by the end of that period, even including acceptable natural regeneration. Of the promising species, 17 were introduced (Marrero 1948, 1950). These results indicate an urgent need to recognize the degraded nature of many planting sites, a factor that may transcend climatic matching in selecting species (Marrero 1950a).

Holdridge's life zones (Holdridge 1967) can be used for first approximations of homoclimes and the species native to each. A study covering central and northern South America (Falla 1968) grouped species by their gross climatic tolerances (table 5–14). It is apparent, however, that some species that are grouped together are not natural associates. This discrepancy may result only from the annual total, not from the season of rainfall, being considered.

The sites on which trees grow fastest may or may not be the most productive in terms of quality. An analysis of *P. caribaea* productivity in Queensland, Australia, (Smith, W.J., 1973) indicated that rapid growth was accompanied by a reduction in density (table 5–15), a property that could be significant for solid wood or sheet products. For cellulose production, the only disadvantage would be slightly larger bulk. Futhermore, the greater gross dry weight on the good sites may more than compensate for this disadvantage where fiber is the end product.

Seasonality of rainfall is an essential criterion in selecting trees for planting in South America. In Venezuela, Veillon (1960), after determining elevation homoclimates for pines, used monthly rainfall patterns for final matching of species to site. Golfari has used this guide extensively in selecting species and sites for Misiones Province in Argentina, for Brazil, and for tropical America as a whole (Golfari 1961, 1963, 1965, 1967, 1975c; Golfari and Barrett 1967).

Golfari's studies probably have been of greatest value in local species selection in tropical America. With Thornthwaite's water balance calculations (Thornthwaite and Mather 1957), pines could be selected for subtropical Puerto Piray, Argentina (Golfari and Barrett 1967). Similar predictions using species site maps were completed for many states of Brazil (Golfari 1967). For *P. elliottii,* Golfari (1968–69) measured 186 plantations to make site-index curves based on mean stand height at age 25, which ranged from 11 to 27 m. His water-balance technique was extended to eucalypts as well as conifers and used eventually in the States of Bahia, Espiritu Santo, Goias, Matto Grosso, Minas Gerais, Parana, Rio Grande do Sul, and Santa Catarina (Golfari 1975c, 1978a, 1978b).

Matching species to sites has improved markedly in recent years, thanks to expanding literature. However, visiting source areas to observe the species in their native environments and to obtain unpublished details about them is still generally justifiable. Navarro de Andrade's (1939) visit to Australia led to the subsequent spectacular

Table 5–14.—Tropical tree species adaptation by life zones in central and northern South America

Species	Lower montane			Montane		
	Dry	Moist	Wet	Moist	Wet	Rain
Acacia decurrens		x	x			
Cupressus lusitanica		x	x	x	x	
Eucalyptus globulus	x					
Pinus caribaea		x				
P. elliottii		x				
P. patula	x	x	x			x
P. radiata	x			x	x	
P. taeda		x	x	x	x	

Source: Falla 1968.

tree-planting program in Brazil. Loock's (1950) studies of Mexican and Central American pines and seed collections for South Africa underlie much of the early success with these species in Africa. Golfari's (1961) trips to the southern pinery of the United States (searching for homoclime provenances of *P. elliottii* and *P. taeda* for Celulosa, Argentina) and to Australia and Timor (for Aracruz, Brazil) are additional examples of the value of firsthand observations.

Experience in Puerto Rico has shown that species selection involves more than matching broad classes of climates, soils, and products. Performance of tree species that appear to qualify on all of those counts varies greatly with local topography and particularly with the degree of soil degradation (Marrero 1950a). Certain species grow best on convex topography (well drained), and others on concave topography (humidity retaining). As planting progresses, these differences are certain to influence the selection of species or provenances.

Present vegetation may be a clue to species choice. Lamb (1968c), after wide travels in America, concluded that pines are a safe bet for trials on extensive grasslands in the Amazon, Guyana, Suriname, Central America, Cuba, and the Bahamas. Subsequent experience seems to bear him out. Baur (1964a) also recognized that on the periphery of what may have been a rain forest, the effects of fire may leave the site productive only for *Eucalyptus* or *Pinus*.

Wherever many plantations of the same species have attained advanced age, site-index curves should be developed to classify sites in terms of tree growth. From the curves derived by exponential regressions of height over age, the index of any site can be determined from the age and height of sample trees.

Variation Within Species. Genetic variation within a species may affect productivity as much as variation among species.

Table 5–15.—Site effects on *Pinus caribaea* productivity in Queensland, Australia

Site index[a] (m)	Merchantable volume (m^3/ha)	Dry weight (t/ha)	Basic wood density (g/cm^3)
21–25	200	95	.473
26–30	258	121	.470
31–35	290	132	.454

Source: Smith, W.J. 1973.

[a]Height at 18.5 years.

Ideally, the species-selection process should compare all the variants of each species. Because all variants are not usually known at the outset of species testing, first selections are tentative. Genetic manipulation may improve the variants of any species. This potential should not be overlooked during the initial selection of species and should be continually pursued thereafter. The use of seeds from selected and improved sources may increase growth rates as much as or more than silvicultural techniques (Donald 1979).

Types of morphological variation among eight sources of teak detected early in Java (Coster and Eidmann 1934) included differences at 1 year ranging from early height growth and branching to almost none.

In classifying the pines of Mexico, Martinez (1948) concluded that in addition to 37 species, there were 21 varieties and 8 forms that were morphologically distinct from the typical species. Loock (1950) also recognized 18 varieties and 9 forms. Critchfield and Little (1966) mapped 36 species in Mexico and referred to additional varieties and subspecies that were not adequately reported for mapping.

Within the natural range of *P. caribaea hondurensis* in Belize, variation within species is evident (McWilliams and Richards 1955). Not only are there two geographically distinct populations, one coastal and one montane, but in the mountains, the trees range in form from good on granitic areas to small and misshapen on exposed quartz and shale ridges. A comparison of three nearby provenances of *P. caribaea hondurensis* showed a wide variation in windfirmness and foxtailing and illustrated the importance of careful selection and testing (Evans 1992).

Tests with different provenances of *P. caribaea* at Monte Dourado, Brazil, disclosed significant differences at age 6 in height, diameter, straightness, forking, branch number, branch angle, wood density, volume growth, and cone production (Woessner 1981a). Of 16 provenances, the 4 best outproduced the worst in biomass by 26 percent. Selecting a seed source from Guanaja Istaul, Honduras, instead of Poptun, Guatemala, promised to increase yield 42 t/ha (Woessner 1981a). Foxtailing can also be reduced. Although accentuated by uniform rainfall, it is strongly inherent and may be largely eliminated through selection (Kozlowski and Greathouse 1970). With *Gmelina,* improved straightness and higher wood density appear attainable through selection of provenances.

A need for obtaining seeds from known sources is generally recognized. Tests of *P. kesiya, P. merkusii,* and *P. oocarpa* in South Africa showed highly variable (and generally poor) form from unselected seeds (Marsh 1972).

Selecting the larger seedlings from a single source of *P. elliottii* in a Brazilian nursery had a significant effect on later productivity (Shimizu and others 1977b). Selecting 1 seedling out of 3,500 in the nursery at age 9 months yielded a group of seedlings that maintained height superiority in absolute terms for 3 years.

Variation in *P. oocarpa* led to the recognition of the variety *ochoterenai,* which has been tested separately and, on some sites, found superior in early growth in Argentina (Molfino and Vairetti 1972) and in Ivory Coast (Goudet 1975).

Significant within-species variations have been found in *P. kesiya* and *P. merkusii* in Papua New Guinea (Howcraft and Davidson 1973a, 1973b). *Pinus merkusii* from Cambodian seeds had a grass stage, an early period of apparent dormancy. Trees from two Sumatran sources varied sufficiently in height at 3 years to indicate a need to discriminate among provenances. By 4.2 years, *P. kesiya* from what is now Malagasy had grown to a mean height of 7.6 m versus 5.2 m for trees from a Thai source and 6.3 m for trees from Philippine seeds. The difference in growth between the Malagasy and Thai provenances was highly significant.

Eight regional races of *Araucaria cunninghamii* have been identified within the natural range of the species (Reilly 1974). They differ significantly in growth rate, stem straightness, and tendency to develop multiple leaders and in branch, bark, and needle characteristics.

Pryor (1978) points out some qualities of the eucalypts that offer opportunities for genetic improvement. There are some 450 distinct species and numerous variants. They comprise the arborescent vegetation of more than half of Australia and, to a limited extent, appear in Celebes, the Lesser Sunda Islands, Mindanao, Papua New Guinea, and Timor. The genus reproduces primarily by random outbreeding, depending heavily on insect pollination.

Different provenances of *E. camaldulensis,* one of the most widespread species of Australia, were found highly variable in six locations in Nigeria (Jackson 1973). Provenances from regions with pronounced summer rains grew best for the first 5 years. The highest tree volume averages were triple the lowest.

Golfari's studies (1977) of *Eucalyptus* in Brazil have shown that different introduced provenances may appear and perform like different species. He cites studies of 35 provenances of *E. camaldulensis,* indicating that for the cerrado regions of Goias, Matto Grosso, and Minas Gerais, seeds from certain areas in northern Australia produce trees superior to those from other provenances. In the caatinga region of Rio Grande del Norte, on the other hand, provenances from other parts of Australia with extreme droughts are required. Only one provenance—from Atherton, Queensland—produced trees resistant to the stem canker, *Diaporthe cubensis.* Progeny from Brazil's earliest plantations, which came from provenances south of Sydney (lat. 34° S.), have been found unsuited to the more tropical latitudes of Brazil. Unfortunately, early plantations of different species of *Eucalyptus* in Brazil were located side by side, so that hybridization and unpredictable progeny resulted.

At Aracruz, Brazil, local sources of *E. "alba"* and *E. saligna* proved susceptible to the canker, *D. cubensis* (Evans 1992). *Eucalyptus grandis,* from latitude 26° to 31° S. in Australia, was also susceptible to this pathogen. The problem was solved by using *E. grandis* seeds collected at latitude 17° S. in Queensland, a provenance that so far has proven to be canker resistant.

At Monte Dourado, Para, Brazil, on the Amazon, early results of provenance tests with *E. deglupta* suggested a genetic gain in height growth of at least 30 percent (Woessner 1980a). Success has been achieved in reducing the susceptibility of *Eucalyptus* to canker farther south at Aracruz by using seeds only from sites environmentally similar to the sites being planted (Campinhas and Ikemori 1977).

In 1973, Golfari's findings led to an exemplary program of provenance testing in which plots of 36 species and 406 geographical provenances of *Eucalyptus* and 4 species and 36 geographical provenances of *Pinus* were established on 46 sites in 5 states of central Brazil (Golfari 1978b). Similar trials in Colombia with 44 provenances of *E. grandis,* 11 provenances of *E. viminalis,* 25 provenances of *E. saligna,* and 43 provenances of *E. globulus* are under way; each plot is sufficiently isolated to permit collection of the best seeds to use as improved seed sources (Ladrach 1980).

A notable example of intraspecific variation is that of *Leucaena leucocephala* (Brewbaker 1975, Brewbaker and others 1972, Hutton and Bonner 1960). Yields in Hawaii from four 2-month harvests of four strains showed the following variation by source: Hawaii, 1.5 kg/ha; Guatemala, 5.5; El Salvador, 6.6; and Peru, 12.6. Another test in Hawaii of 90 strains of this species showed marked variation with day length, growth habit, leaf characteristics, pod length, pubescence, number of seeds, ultimate tree size, and mimosine content. What has become Hawaiian Giant K8 *Leucaena* was an arboreal, summer-flowering variant received from Zacatecas, Mexico. It proved to have exceptional vegetative vigor and aggressive arboreal growth with larger leaves, leaflets, flowers, pods, and seeds than common strains. At a spacing of 1.3 m, this variety produced trees averaging 24 cm in d.b.h. and 17 m in height at 6 years of age.

An intermediate form of *Swietenia,* apparently a cross of *S. macrophylla* and *S. mahagoni,* has appeared in many tropical countries where these two species have been grown in close proximity. Tree form is intermediate, growth on dry sites is apparently more rapid than that of *S. mahagoni,* and drought tolerance is superior to that of *S. macrophylla* (Geary and others 1972).

Tree Improvement. Until 1910, silviculture was chiefly concerned with cultural techniques and the favoring of what were thought to be the best phenotypes (Melchior 1969). Since then, the application of genetics—through provenance selection, hybridization, mutation, and polyploidy—has been directed toward increasing timber yields above what is possible purely by silvicultural treatment. In the Tropics, however, the development of different genotypes of tree species suited for planting has hardly begun, despite prospects for gains in yields well beyond the yields of present forests (Namkoong and others 1980). For example, mass selection of *Eucalyptus* in Brazil has shown it possible to nearly double yields (Venkatesh 1976), with yields of more than 100 m^3/ha/yr foreseen. Genetic betterment of pines is to be expected in terms of straightness, fork reduction, and volume and value growth. Increased tolerance of poor sites and resistance to pests and diseases may also be produced through tree breeding.

Burley (1969), Jones (1966), Melchior (1969), and Wright (1976) list steps to be followed in the tree-improvement process once the species has been selected:

1. Conduct provenance trials.
   a. Short-term, results before first thinning, rangewide comparisons
   b. Medium-term (to one-third or one-half of the rotation), early growth performance, form, and wood quality
   c. Long-term, few provenances, one-half or more of the rotation, fruiting, yield comparisons

2. Establish plantations.

3. Rigorously select superior phenotypes from plantations in a uniform environment so that nongenetic effects are minimal.

4. Identify areas for seed production from the best stands.

5. Establish initial seed orchards from grafted, superior stock.

6. Test progeny of trees for performance and wood-quality characteristics also possessed by the parents.

7. Establish progressive seed orchards, selected from step 6.

8. Begin second and later cycles of selection and control.

Provenance trials are conducted to identify as quickly and economically as possible those provenances yielding well-adapted and productive forests (Burley 1969). Productivity may not always mean rapid growth, however. It might mean survival, resistance to adverse environmental factors or pests, wood quality, or seed productivity.

A second objective of provenance trials is to establish local seed-production stands. Seed-production areas are a relatively cheap means of obtaining seeds of known origin almost immediately (Squillace 1970). Good stands of trees are selected and thinned to favor the best ones. Other cultural practices to stimulate seed production may be used. For example, annual applications of NPK fertilizer to *P. elliottii* have significantly increased cone crops in the southeastern United States (Shoulders 1968). Tree selection for seeds should be done by weighting numerically coded traits. The extent of possible genetic gain depends strongly on the degree of genetic variation in the population, the uniformity of the environmental conditions, and the intensity of selection.

Zobel (1972) emphasized the need for concern about the breadth of the genetic base during genetic selection. He pointed out that it is not possible to preserve all natural genotypes; there will be some loss of genetic potential for certain characteristics following selection and breeding. Even 300 distinct clones may not be enough to prevent long-term deterioration of seed production. Nevertheless, Zobel found that careful selection of the traits to be retained need not seriously narrow the genetic base. In fact, a well-planned operation can do the opposite, bringing together distant provenances to establish new combinations. Zobel concluded that the search is not for highly specific clones for each condition, but rather for broad groups of superior combinations that are widely adaptable. He foresaw the development of rapidly growing clones with low nutrient requirements.

Seed orchards are fundamental to progress in genetic tree improvement and should be located on good sites and isolated from pollen contamination (Zobel and others 1958). For pines, isolation of at least 150 m is desirable. The selection of scions for use in seed orchards should consider the following factors (Zobel and others 1958):

- Especially suitable wood characteristics

- Silviculturally desirable morphological and physiological characteristics

- Growth rates

- Genetically (rather than environmentally) controlled desirable characteristics

- Proved genetic worth (or at least with progeny tests in progress).

Heybroek (1978) noted some difficulties experienced with seed orchards. Many tree families fail to produce enough male or female flowers. Thus, the yield of saw may come from a few individuals, defeating the plan for a broad genetic base. Heybroek saw an inherent antagonism between seed production and vegetative growth. He believed production of the bulk of the seeds in orchards by a few clones should be minimized in the selection of the climate, soil, and cultural practices for the orchards. Another danger lies in the gradual selection of the best clones at the expense of diversity. This he saw as leading toward the planting of large areas with trees of minimum genetic variations. Haybroek reported few firm data indicating a greater difference in production from genetic variation than from genetic uniformity. But he speculated that a mixture might produce more because of varied resistance to the vicissitudes of climate and other factors.

Eighteen provenances of *Swietenia* were collected from Mexico to Panama by the Institute of Tropical Forestry in Puerto Rico from 1966 to 1967. A gene bank has been established and adaptability tests conducted in Puerto Rico and the U.S. Virgin Islands.

The spectacular growth of *Eucalyptus* at Aracruz, Brazil, resulted from the careful testing of more than 1,000 provenances of 37 species (Kalish 1979a). Based on 12 criteria, including an underbark volume of at least 1 m^3 solid at 7 years, foresters selected 1,500 superior trees from among 20 million of the oldest trees.

By 1972, provenance trials of many pines were under way in different tropical countries (Wood 1972). So far it has been found that, generally, the best provenance of *P. oocarpa* is the *ochoterenai* variety from Honduras, that the best *P. merkusii* is from the islands, not the mainland *(P. merkusiana),* and the best *P. kesiya* is generally from Vietnam provenances, not the Philippines. Teak trials promise better provenances for high altitudes and dry zones.

By 1974, provenance trials of 10 major tree species were being internationally coordinated (Wood 1974). Included were 30 provenances of *P. caribaea,* 25 of *P. oocarpa,* 21 of *P. kesiya,* 11 of *P. merkusii,* and 10 of *Cedrela odorata.* Other species included *E. deglupta, E. grandis,* and *Tectona grandis.* The *P. caribaea* provenances, collected and coordinated by the United Kingdom in cooperation with the Food and Agriculture Organization, included 22 provenances in Central America from Belize to Nicaragua, 7 from Cuba, and 1 from Andros Island in the Bahamas (Kemp 1973a). Shortly thereafter, under the same auspices, 25 provenances of *P. oocarpa* were collected from Belize to Nicaragua. Thirty tropical countries participated in the resulting provenance studies (Kemp 1973b).

The urgency of collecting germplasm before deforestation wipes it out is paramount in tropical countries (Kemp 1978, Wood 1976). Some valuable species have already become scarce. For example, few seed sources of *Taiwania* remain (Hung 1969). Kemp saw a particularly serious prospect in rain forests where so many species are affected. Forest reserves are not an entirely satisfactory solution either because they cannot possibly contain all variants. Also, as Kemp pointed out, if reserves are used for multiple purposes, even with stable protection, not all species are favored.

Assessments of the international *P. caribaea* and *P. oocarpa* provenance trials are beginning to show some constant relations (Greaves 1980, 1981b). The *P. caribaea* results come from 205 assessments of 113 trials in 26 countries, and the *P. oocarpa* results are from 166 assessments of 77 trials in 24 countries. A year after planting, evident in *P. oocarpa* were provenance variations that affect choice of seed source and plantation management. For *P. caribaea,* the appearance of such variations took 3 to 4 years. Trials show that the most vigorous variety of *P. caribaea* is *hondurensis* and that the least is *bahamensis*. But *bahamensis* is best and *hondurensis* worst in stem and crown form and resistance to frost damage. Among the *hondurensis* provenances, those from the lowlands offer best stem and crown form, growth, and windfirmness. Provenances from higher and drier inland localities flower earlier (in 3.5 years) and have fewer foxtails but produce needleless shoots and dieback on lowland equatorial sites. At age 5, the most vigorous and windfirm trees are from the southern coastal regions of Honduras and Nicaragua, but some have extensive foxtailing. For *P. oocarpa,* foxtails were produced only by the provenances from Mountain Pine Ridge, Belize.

Numerous independent provenance tests are under way in different tropical countries. In 1968, a test of 12 provenances of *A. angustifolia* was undertaken in Brazil (Baldanzi and Araujo 1971). By the third year, differences in height growth were becoming apparent. From 1972 to 1976 in Nicaragua, a test of 134 forest species and provenances was undertaken (Evans 1977). Early results suggested that several species may be adapted to different regions for various purposes.

The process of hybridizing selected genotypes holds great promise. The exceptionally high yields of *Eucalyptus* at Aracruz, Brazil, come in part from hybridizing *E. grandis* and *E. urophylla* (Kalish 1979a), a hybrid now used at Jari as well.

Genetically improved trees make intensive management attractive. But trees of great growth potential may tax a site more than less productive, native stands (Wollum and Davey 1975). Thus, these advances in yields may increase the drain on the nutrient resources of the site and possibly affect succeeding crops.

A well-planned tree-improvement program for Amazonia was proposed by Pitcher (1976). It called initially for elimination trials to screen out all but the best species, followed by performance trials of the best species, and then, a third elimination of the poorer species and provenances. Finally tree-improvement efforts, based on the results of these trials, would be directed toward: (1) increasing growth rates, (2) improving form and quality, and (3) determining heritability of characteristics of economic value or for future genetic improvement.

Pitcher favored "plus-tree" (phenotype judged superior in some quality) selection for the few species that have been planted in Amazonia in areas larger than 50 ha but convincingly argued against attempting to make such selections in native forests. One of his most telling points was the variability of growing conditions in natural forests that would confound any attempt to attribute tree superiority to genetic characteristics. He foresaw the greatest genetic gains in nurseries, from mass selection with intensities of 1/1,000 to 1/10,000. He further recommended that tree improvement be concentrated on only a few species, including: *Carapa guianensis, Eucalyptus* spp., *G. arborea, P. caribaea, Platonia insignis, Schefflera morototoni, Schizolobium amazonicum, Terminalia ivorensis,* and *V. surinamensis.*

Tests with open-pollinated *P. taeda* families showed the superiority in volume of selected trees at 20 years, based on selection at 5, 10, and 15 years (Lambeth and others 1983). When the selection was made on height, the best one-third of the trees had a volume superiority of 15 to 18 percent. Selection of only the top three individuals gave a volume superiority of 58 to 64 percent. When the selections were made on the basis of volume instead of height, the superiority for the best one-third of the trees was 16 to 19 percent and for the best three, 54 to 102 percent. Selections made at age 5 were generally as effective as at age 15.

A recent definitive work on tree improvement by Zobel and Talbert (1984) is worldwide in scope but treats the Tropics in detail. It is an extremely useful reference for species or provenance selection and the development of improved races. The concepts developed include advantages and limitations of tree improvement, where and when to attempt tree improvement, and essentials of an improvement program. Chapters deal with provenances, seed sources, and exotics; selection in natural stands and unimproved plantations; selection and breeding for resistance to diseases, insects, and adverse environments; vegetative propagation; wood quality; and the economics of tree improvement.

Planting Progress

Information from reports from around the tropical world and covering the early and recent history of forest planting is presented in appendix H. This account is far from complete but presents significant developments, first from the Eastern Hemisphere, where efforts began, and ending with tropical America.

General reports give some evidence of the relative rates of tree planting in different tropical areas (Anon. 1965c, 1968c, 1993b). What were classified in 1964 as rapidly growing plantations covered 700,000 ha in Brazil and 750,000 ha in Argentina, Chile, and Uruguay combined. In Africa, there were 710,000 ha, and in the Asia-Pacific region, 1,650,000 ha. Of the tropical total, 25 percent were coniferous, chiefly *A. angustifolia, P. patula,* and *P. radiata.* Among the broadleafs, *Eucalyptus* covered 1.3 million ha, and *Tectona grandis,* 1 million ha. Establishment rates for fast-growing plantations in 1965 were estimated to be 150,000 ha/yr in Latin America, 120,000 ha/yr in the Asia-Pacific region, and 50,000 ha/yr in Africa (Anon. 1965f).

Incentives provided for planting in the Tropics in 1968 included credit, tax exemption, tax reduction, technical assistance, cheap planting stock, and the formation of cooperatives. Difficulties included inadequate public support, weak forest departments, lack of planning, insufficient seed supply, and inadequate knowledge of species and provenances.

By 1990, 8.6 million ha in tropical America were devoted to plantations (table 5–16; Anon. 1993b), only about 0.5 percent of the total land area. About 373,000 ha are planted annually in tropical America, only 4 percent of the area already planted. Because replanting is included, probably less than half of this amount constitutes a net increase in the plantation area.

The plantation area is about equally divided between industrial and nonindustrial (the farmer producing

Table 5–16.—Forest plantations in the Tropics, 1990 (thousand ha)

Country	National land area	Existing plantations	Annual planting rate[a] 1980–90
Belize	2,280	3	0.1
Bolivia	108,438	40	1.4
Brazil	845,651	7,000	279.2
Colombia	103,870	180	12.7
Costa Rica	5,106	40	3.7
Cuba	10,982	350	19.3
Dominican Republic	4,838	10	0.4
Ecuador	27,684	64	2.1
El Salvador	2,085	6	0.5
Guatemala	10,843	40	2.5
Guyana	19,685	12	1.1
French Guiana	8,815	0	0.0
Haiti	2,756	12	1.1
Honduras	11,189	4	0.4
Jamaica	1,083	21	0.8
Mexico	190,869	155	7.5
Nicaragua	11,875	20	1.8
Panama	7,599	9	0.5
Paraguay	39,730	13	1.0
Peru	128,000	263	12.6
Suriname	15,600	12	0.4
Trinidad/Tobago	513	18	0.2
Venezuela	88,205	362	23.8
Total America	**1,650,147**	**8,636**	**373.0**
Africa	2,236,063	3,000	129.5
Asia-Pacific	892,137	32,153	2,104.1
Grand Total	**4,778,347**	**43,789**	**2,606.5**

Source: Anon. 1993a.
[a]Plantations planted per year.

timber, fuelwood, rural poles and posts, nonwood products such as palm hearts and forest tree fruits, and soil protection) (Lanly 1981; table 5–17). Rubber, palm oil, coconut, and agricultural shade plantings and fruit orchards are excluded.

Most of the industrial plantations are coniferous, whereas nonindustrial plantations are mostly fast-growing, broadleaf species. The planting rate, overall, is about one-eighth of the area deforested each year (Anon. 1993b).

Known and estimated planted areas in tropical America for the major species, up to 1980, are shown in table 5–18 (Panday 1983). Evans (1986) summarized the progress of forest planting between 1978 and 1985 as follows:

- Probably more than 1 million ha are planted per year.
- Most new plantations are for social and environmental rather than industrial purposes.

Table 5–17.—Plantation establishment in tropical America, 1985 (thousand ha)

Purpose and species	Planted area, 1985
Industrial	
Broadleaf	3,979
Fast-growing species[a]	1,393
Other[b]	183
Nonindustrial	
Broadleaf	3,314
Fast-growing species[a]	2,619
Other[b]	613
Conifers	82
Total	**7,293**

Source: Lanly 1981.
[a]Mean annual increment more than 12 m^3/ha/yr.
[b]Mean annual increment less than 12 m^3/ha/yr.

Table 5–18.—Planted areas in tropical America by species, 1980 (thousand ha)

	Planted Areas	
Species	Known	Estimated
Eucalyptus saligna	674	702
Pinus elliottii	281	281
P. patula	199	199
E. grandis	189	192
P. caribaea	137	337
E. globulus	118	131
Gmelina arborea	76	86
Cupressus lusitanica	26	48
Casuarina equisetifolia	20	20
Others	93	775
Total	**1,813**	**2,771**

Source: Panday 1983.

- Arid-zone planting for fodder, firewood, and fencing has greatly increased.

- New planting must continue to increase, with emphasis on social objectives if increasing hardships among the rural poor are to be avoided.

The recent rate of reforestation will clearly not offset deforestation (table 5–19; Anon. 1985f). An overall planting rate one-tenth the rate of deforestation might be adequate to sustain timber yields because of the much higher production rates for successful plantations. However, the planting rate is far below 10 percent of the deforestation rate in nearly all countries, and the plantations, generally monocultures of exotics, whatever their industrial potential, are, in the ecological sense, no tradeoff for the loss of primary ecosystems (table 5–19).

Tropical forest planting has nevertheless increased rapidly since the 1940s, with more than 60 percent of the plantations established during the 1970s (Brown and others 1986). The total biomass of the plantations at that time was estimated to be between 650 million and 2.22 billion t and constituted an atmospheric C sink of between 30 and 110 million t/yr, possibly adequate to balance the C released from harvesting forests and other land uses in the Temperate Zone (Brown and others 1986).

Table 5–19.—Planting rate relative to major deforestation in tropical America, 1980–90 (thousand ha)

Country	Annual deforestation	Annual forest planting
Bolivia	625	1.4
Brazil	3,680	279.2
Colombia	367	12.7
Costa Rica	50	3.7
Ecuador	238	2.1
Guatemala	81	2.5
Honduras	112	0.4
Mexico	678	7.5
Nicaragua	124	1.8
Paraguay	402	1.0
Peru	271	12.6
Venezuela	599	23.8

Source: Anon. 1993c